

METEOROLOGICAL FACTORS AFFECTING AIRPORT OPERATIONS  
DURING THE WINTER SEASON IN THE MIDWEST

A THESIS

SUBMITTED TO THE GRADUATE SCHOOL  
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE  
MASTER OF SCIENCE

BY

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BALL STATE UNIVERSITY

MUNCIE, INDIANA

JULY 2017

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## **ABSTRACT**

**THESIS:** Meteorological Factors affecting Airport Operations during the Winter Season in the Midwest

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During the coldest months of the year, weather systems bring a variety of winter weather to most of the continental United States in the form of snow, sleet, and freezing rain, which along with strong winds, low clouds, and reduced visibilities, may create dangerous conditions. These weather conditions can create major disruptions in air travel, leading to delays and cancellations of hundreds or thousands of flights, thus affecting the plans of millions of travelers. To assess the specific meteorological factors that prompt flight delays and cancellations in the Midwest region of the United States during wintertime, a comprehensive study was performed on nine of the largest airports (by passenger boardings) in the area.

Flight delay and cancellation data from eleven winter seasons (2005–06 to 2015–16) were collected from the Bureau of Transportations Statistics (BTS) and analyzed along with climatological data from the National Centers for Environmental Information (NCEI). A classification scheme was developed, and each flight was categorized according to the meteorological factor that could have prompted its delay. The results of the study revealed that

visibility was the main meteorological factor affecting Midwestern airports, with low ceilings a close second. Blizzards were the main cause for flight cancellations. Two case studies, one of a lake-effect snow event that caused major delays, and another of a large blizzard that prompted severe disruptions across the area, were performed as well.

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## **CHAPTER 1: INTRODUCTION**

Studies by the Federal Aviation Administration's (FAA's) Observation Network have shown that weather is the largest cause of air traffic delays in the National Airspace System (NAS), accounting for 69% of all air traffic delays from 2008 to 2013 (FAA 2017). The FAA defines a delayed flight as one in which an aircraft departs at least 15 minutes later than its originally scheduled time. Furthermore, the portion of delays due to weather represented nearly 10 million minutes in 2013. However, if weather conditions deteriorate to such an extent that it may become dangerous for planes to fly, flights could get cancelled instead of delayed. Winter is the season with the most cancellations due to weather; in fact, during the 2010–11 winter season, between 1 November and 11 February, a total of 86,000 flights were either delayed or canceled throughout the country Bureau of Transportation Statistics (BTS; 2017). During the cold season, weather systems bring snow, sleet, or freezing rain to most of the continental United States, excluding extreme southern areas of Florida, Arizona, and California due to their warmer and drier climates. Even southern cities such as Atlanta, Dallas, and Memphis have recorded some type of frozen precipitation, per climate records by the National Centers for Environmental Information (NCEI; 2017), but in lesser amounts than that experienced by more northern cities such as New York, Chicago, Minneapolis, or Buffalo. In this study, flight data were compared with hourly weather observations to determine the frequency by which different wintertime meteorological factors resulted in delays or cancellations of flights in major Midwestern airports.

Flight delays and cancellations affect all individuals and institutions involved in the commercial flight process. A prime example of this is a passenger traveling for a business meeting

who experiences a flight delay or cancellation, which would effectively disrupt his or her professional schedule, as the meeting destination may not be reached on time. From the airlines' perspective, officials may have to invest additional funds to plow runways after a snowstorm, which would prompt a rise in operational costs. In fact, cancellations from storms over the entire month of February 2010 were estimated to have cost \$80–100 million nationwide, with an additional estimated \$18.8 million from delays (Guarino and Firestone 2011).

Given that New York City, with an estimated population of 8.5 million in 2015 (U.S. Census 2017), is the country's most populated city, and that major cities like Boston, Philadelphia, and Washington, D.C., lie along the heavily populated northeastern corridor, past studies focused on flight delays and cancellations in airports located within this area; the majority classified the impacts of winter storms at large airports, and in the cities in which they are located. For instance, Cerruti and Decker (2011) proposed the Local Winter Storm Scale (LWSS) and applied it to 15 winter seasons at Newark-Liberty International Airport in Newark, New Jersey in order to classify each winter storm that affected that airport. Kocin and Uccellini (2004) developed the Northeast Snowfall Impact Scale (NESIS), which focused on the amount of snow that fell and mapped it onto the population density that experienced the snow. As most of these studies focused solely on the impacts of a single storm on the Northeast's aviation system, little research has been done outside of this geographical region. Likewise, there has been a lack of research into the meteorological factors that prompt disruptions in airport operations; flight delays and cancellations are impacts of a winter storm, and are used to measure how disruptive the storm is, but little is known about the specific weather conditions that caused the delays and cancellations. Along this line, Robinson (1989) performed a study on winter weather-related

delays and cancellations at the Atlanta Hartsfield-Jackson International Airport, but data were scarce and only encompassed three winter seasons.

The purpose of this study is to identify the meteorological factors that prompt flight delays and cancellations during the winter season in the Midwest region of the United States. In order to achieve this, flight delay and cancellation data, along with meteorological data for several of the Midwest's largest airports, were retrieved and analyzed. After assessing the weather conditions at and around the scheduled departure time, the meteorological factor(s) that prompted each flight's delay was (were) determined. In the case of cancellations, a broad, synoptic-scale analysis was made to determine what type of system prompted them.

Since snow is common in northern latitudes during winter, one could hypothesize that it is the main factor affecting airport operations during that season, and that it plays a big role in the process of weather-related flight and cancellations. However, snow could be only one of multiple factors. Aside from plowing runways, airplanes may need to be de-iced, and maybe more importantly, weather conditions should allow pilots to taxi, takeoff, and land without any problem. Any single (or a combination of) meteorological factor(s) may be responsible for weather-related disruptions in airport operations during the coldest season of the year.

## **CHAPTER 2: LITERATURE REVIEW**

Every year millions of Americans travel by plane for either business, leisure, or to visit family across the country. According to the Bureau of Transportation Statistics (BTS 2017), in 2015 alone there were 679 million enplaned domestic passengers. In addition to summer, winter is the year's busiest travel season, not only because it contains several holidays, including Hanukkah, Christmas, and New Year's Day, but also schools and universities are on winter break, which presents an opportunity for families to travel. The number of long-distance trips (defined as a destination at least 50 miles away) during the Christmas/New Year's holiday period increases by 23 percent compared to the average number of these trips during the remainder of the year (BTS 2017). Although only 5 to 6 percent of holiday trips are by air, the frequency and strength of winter storms can seriously disrupt travel for passengers, airports, and airlines. This means that hundreds—and sometimes thousands—of flights are cancelled or delayed due to winter weather. In fact, in preparation for powerful winter storms, some airlines cancel flights before the actual storm arrives at the airport, which helps not only the airline, but also the airport itself, as it aids in the management process once the storm ends and regular operations resume (Mouawad 2011).

In 2000, the U.S. Department of Transportation (DOT) created the Air Carrier On-Time Reporting Advisory Committee under BTS's jurisdiction. This committee's main task was to consider changes to the on-time reporting system so that the public would have clear information about the nature and sources of airline delays and cancellations, which resulted in the creation of a reporting framework for collecting information about the causes of airline delays and cancellations (BTS 2017). The recommendations for changes were presented in late 2001, and after reviews by the DOT, BTS, and aviation community, they came into effect in the fall of 2002.

These new changes require commercial airlines to report information on causes of delays, which they started doing in June 2003.

## **2.1 Reasons for Flight Delays and Cancellations**

The FAA defines a delayed flight as anytime an aircraft departs at least 15 minutes later than scheduled, while a cancellation is any scheduled flight that will not depart at all from the airport. As the impact on a specific airport's operation depends on the physical configuration and orientation of its runways (Chin et al. 1997), each airline is responsible for deciding whether a flight may be delayed or cancelled. Flight delays and cancellations may occur at any time, and at any airport, due to several reasons, including but not limited to late-aircraft arrivals, heavy air traffic, delays at security checkpoints, airline operations, and weather. Heavy air traffic and delays at security checkpoints may have a greater impact during holidays or historically busy travel days like Memorial Day, Labor Day, Thanksgiving, Christmas, and most of the summer season. Aircraft crew arriving late to an airport, aircraft mechanical problems, or delayed baggage may contribute to late-aircraft arrivals and airline operations delays. Software glitches or outages, which was an unthinkable and an unlikely cause of delays in the early aviation age, is presently one of the most frequently reported reasons why flights are cancelled (Levin and Sasso 2016). In fact, between June 2015 and August 2016, four of the major U.S.-based airlines had to either delay or cancel flights due to technological failures (Jones and Weise 2016).

Weather, however, may affect all four of a flight's phases: terminal, departure, en route, and approach, which would result in different levels of disruptions at airports. Terminal operations, including ramp operations, taxiing between ramp and runway, and the first or final moments of



takeoff or touchdown are key processes when considering the possibility of delaying or cancelling flights (COMET Program 2017).

## **2.2 Weather Delays and Cancellations**

Thunderstorms and convective systems, which can include intense updrafts and downdrafts, lightning, hail, wind shear, and tornadoes, have an adverse impact on aircraft operations (Kulesa 2003). Any of these weather phenomena can cause an aircraft to be re-routed, which often leads to late arrivals, ground-stops (when a plane has been boarded but it is not allowed to takeoff due to adverse weather), or in worst-case scenarios, accidents, such as the 2 July 1994 crash near the Charlotte Douglas International Airport in Charlotte, North Carolina (NTSB 1995). This accident involved USAir's Flight 1016 en route from Columbia, South Carolina to Charlotte, which collided with trees and a private residence after the flight crew decided to continue an approach into severe convective activity that produced a microburst, prompting a rapid loss of aircraft altitude. After realizing what was happening, they tried to regain control of the aircraft, however, due to the strong wind shear, it was impossible to do.

Turbulence caused by non-convective systems is also a major hazard for aircrafts, as it could occur under fair weather conditions, making it prone to go unnoticed until the aircraft enters it; turbulence can be confined to one small area, or it could be randomly widespread. Erratic wind patterns and low clouds which cause visibility reductions can also contribute to flight delays and cancellations throughout the year.

### 2.3 Winter Weather Factors that Impact Flights

In the northern hemisphere, meteorological winter extends from December through February. However, fluctuations in atmospheric patterns and geography may induce winter-like conditions as early as October or as late as April in some places. As temperatures turn colder, frozen precipitation may be experienced in many cities and towns, along with rapid changes in wind patterns and atmospheric pressure, which could create disruptions in daily life activities, including airport operations. For instance, Chin et al. (1997) interviewed different levels of aircraft-air traffic control (ATC) staff and pilots, who indicated that taxiing slows significantly when ground visibility is less than 0.5 mile, or when there is snow or ice on the surface. But during these times, there tends to be considerably less traffic due to precautionary flight cancellations by airlines. There are several weather elements that can impact airport operations during the winter, and are the main reasons why a flight is delayed or cancelled due to weather in the cold season (Table 2.1).

Table 2.1. Main factors affecting airport operations during winter.	
Factor/Reason	Impact on Flights
Cloud ceiling heights	Poor or no visibility of runways and or sky
Precipitation	Runway conditions—snow/ice
Wind direction and speed	Involuntary change of course of plane/may not be able to safely takeoff or land
Icing	Accumulations of frost, snow, and/or freezing rain/drizzle on aircraft surfaces

#### *a. Cloud Ceiling/Visibility*

The International Civil Aviation Organization (ICAO) defines cloud ceiling as the height of the base of the lowest layer of cloud below 6,000 meters covering more than half the sky, as measured from the surface (ICAO 2010). A tall cumulonimbus cloud with a very low base, or a dense layer of stratus clouds near the surface, are common examples of low-lying clouds that could lower the ceiling at an airport, and consequently, impact its operations. A combination of calm winds, a very moist atmosphere, and clear skies may produce thin or dense areas of fog, which are very low-lying clouds that impact both ceiling and visibility.

Visibility, in the meteorological sense, is the greatest distance in a given horizontal direction at which it is just possible to see and identify with the unaided eye, either: 1) in the daytime, a prominent dark object against the sky at the horizon, or 2) at night, a known, preferably unfocused, moderately intense light source (AMS Glossary 2017). However, a distinction is made between this strictly physical definition of visibility and the terminology used by the aviation industry. Specifically, the U.S. aviation industry uses three main terms to describe visibility: surface visibility, control-tower visibility, and runway visual range. The first is basically the same as the meteorological visibility definition, and is taken from a fixed point on the ground either by an individual or an automated sensor. Control-tower visibility is the visibility observed from an airport tower by either an individual or an automated sensor. According to current U.S. weather observing practice, at civil stations, the control-tower visibility becomes the official visibility for the station whenever the surface visibility becomes less than three miles (AMS Glossary 2017). The runway visual range is the range over which the pilot of an aircraft on the center line of a runway can see the runway surface markings, the lights delineating the runway, or can identify its

center line. If any of these is affected by weather, airport operations could be disrupted, leading to delays or cancellations, depending on the magnitude of the on-going weather situation.

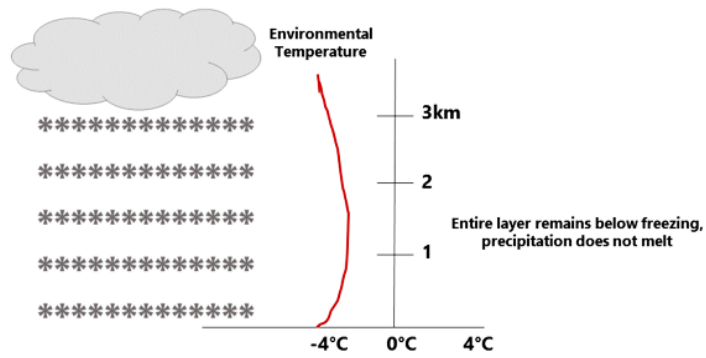
During winter, visibility can be affected not only by fog, but also by blowing snow at an airport or in areas surrounding it. Blowing snow refers to either falling or accumulated snow that is lifted from the surface of the earth by the wind to a height of 6 feet or more above the surface, and blown about in such quantities that horizontal visibility is reduced to less than 11 km (~7 miles; AMS Glossary 2017). Freshly fallen snow is easily disturbed and can be one of the main causes of blowing snow, lowering visibilities to such an extent that aircraft landing operations can be greatly disrupted. In extreme cases, a pilot's visibility may be excellent while approaching the runway up until the aircraft's final touchdown, at which time the runway visual range is reduced abruptly due to the blowing snow (Vickers et al. 2000).

The FAA has developed guidelines for both air controllers and pilots to follow in situations when low ceilings and poor visibility may cause problems. These guidelines, divided into the Visual Meteorological Conditions (VMC) and the Instrument Meteorological Conditions (IMC), consider cloud bases measured in feet and visibility ranges measured in miles. VMC are defined as ceilings of 3000 feet or more and/or visibility of 5 miles or greater. In these cases, most pilots can depart or land with no significant problems, and should follow the Visual Flight Rules to safely depart or land (the pilot must be able to see the ground at all times, and no additional instrument is needed to operate safely). For their part, IMC are defined as any weather than reduces ceilings to 3000 feet or less and/or visibility to 3 miles or less. Due to the difficulty and danger that may present IMC, for a pilot to be able to fly during these instances, he or she must take special training to be certified as an "Instrument-rated pilot" (Houston 2017), and follow the Instrument Flight Rules (IFR). A summary of both VRF and IFR is presented in Table 2.2.

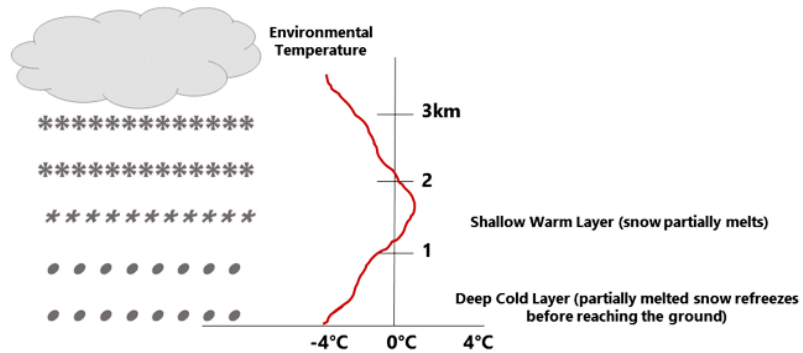
Table 2.2. Main factors affecting airport operations during winter.			
Category	Ceiling (feet)	Condition	Visibility (miles)
Visual Flight Rules (VFR)	Greater than 3000	AND	5 or greater
Marginal Visual Flight Rules (MVFR)	1000 to 3000	AND/OR	3 to 5
Instrument Flight Rules (IFR)	500 to 1000	AND/OR	1 to 3
Low Instrument Flight Rules (LIFR)	Less than 500	AND/OR	Less than 1

*b. Frozen Precipitation*

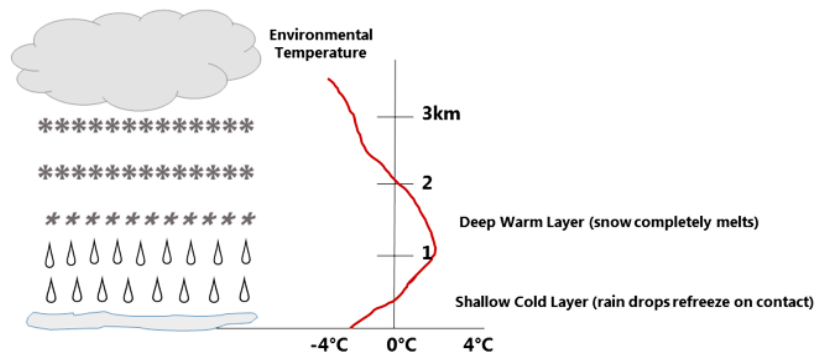
During wintertime, the type of precipitation that falls in an area greatly depends on the atmosphere's vertical temperature profile; the freezing point of water, 0°C, serves as a threshold for frozen precipitation (Figure 2.1). If the entire temperature profile is at or below the freezing point, precipitation will fall as snow, otherwise, it will fall as sleet or rain (Table 2.3), which may or may not freeze upon contact with the surface on which it falls (e.g., roads, sidewalks, power lines or trees).



### SNOW



### SLEET



### FREEZING RAIN

Figure 2.1. Types of winter weather precipitation and their formation process.

Table 2.3. Definition of the main types of precipitation during winter. Taken from the Glossary of Meteorology published by the American Meteorological Society (AMS).

<b>Type of Precipitation</b>	<b>Definition</b>
<b>Snow</b>	Precipitation composed of white or translucent ice crystals, chiefly in complex branch hexagonal form and often agglomerated into snowflakes.
<b>Sleet</b>	Generally transparent, globular, solid grains of ice that have formed from the freezing of raindrops or the refreezing of largely melted snowflakes when falling through a below-freezing layer of air near the earth's surface.
<b>Freezing Rain</b>	Rain that falls in liquid form but freezes upon impact to form a coating of glaze upon the ground and on exposed objects.

As a precautionary measure, the FAA (2017) requires every airport that receives more than 6 inches of snow per year to create a Snow and Ice Control Committee, which oversees the creation of guidelines for winter operations at that airport. For example, the Milwaukee-General Mitchell International Airport 2015–16 Winter Operations Plan’s (2017) main goal “is to provide guidance for Airport Staff on managing safe and efficient airport snow removal operations while simultaneously conveying to stakeholders the Airport’s intentions so that operational decisions can be made accordingly”.

The National Weather Service (NWS) defines heavy snow as snowfall accumulating to 4 inches or more in depth in 12 hours or less, or snowfall accumulating to 6 inches or more in depth

in 24 hours or less. Snow falling at a high rate accompanied by strong winds and low visibility is called a blizzard. The NWS defines a blizzard as a winter storm where the following conditions are expected to prevail for a period of 3 hours or longer: sustained winds or frequent gusts to 35 miles an hour or greater, and considerable falling and/or blowing snow, frequently reducing visibility to less than 0.25 mile (NWS Glossary 2017). Most blizzard events create whiteout conditions in which the horizon and immediate objects are not discernible. In these types of events, airport operations can be affected, as happened during the 26–27 January 1967 Chicago Blizzard, which closed all airports in the city, and stands as Chicago’s all-time greatest snowfall from a single storm at 23.0 inches (NWS Chicago 2017).

Aside from snowfall produced by storm systems, some areas in the United States receive large amounts of frozen precipitation from the meteorological phenomenon known as “lake-effect” snow, which has its own complex mechanism for precipitation development and is also a major contributor to disruptions during the cold season. It particularly affects the downwind areas of the North American Great Lakes during late fall and early winter (Wright et al. 2012), producing large amounts of snow during short periods of time and in relatively small areas. In fact, for some locales near the Great Lakes, lake-effect snowfall accounts for almost half of their total winter precipitation (Scott and Huff 1996). Snowfall rates as large as 30 cm ( $\sim 12$  in.)  $\text{h}^{-1}$  and 75 cm ( $\sim 30$  in.)  $\text{day}^{-1}$  have been observed, as has lightning in some of the most intense cases (Markowski and Richardson 2011). The states of Indiana, Michigan, New York, Pennsylvania, and Ohio are the main areas in the United States that are affected by this phenomenon.

The mechanism for the formation of lake-effect snow is primarily the sharp difference between the temperature of the air and that of the lake surface. Due to its high heat capacity, water tends to take a longer time to cool off than the air directly above it, leading to large temperature



gradients between air and water. Niziol et al. (1995) mentions that a 13°C temperature difference is between the water and the 850 mb level is necessary to produce lake effect snow. In the mid-latitudes, the westerlies are the prevailing winds (Mayes and Hughes 2004), which in the winter bring cold air from the Arctic, creating a prime scenario for lake-effect snow. During late fall and early winter, as cold air moves out across the warmer body of water, heat and moisture are mixed into the near-surface layer, with it becoming less dense than the colder air surrounding it, causing it to become more buoyant and therefore ascend. Precipitation from the resulting convective clouds will fall in the form of snow on the leeward side of the lake, creating bands of snow, and sometimes heavy snow squalls (Figure 2.2). If the area immediately surrounding the lake is relatively high in elevation, or there are hills nearby, orographic lifting will greatly increase snow totals. Once the surface of the lakes has frozen, usually by mid-February, the lake-effect phenomenon will cease, as the water is at or near the same temperature as the air.

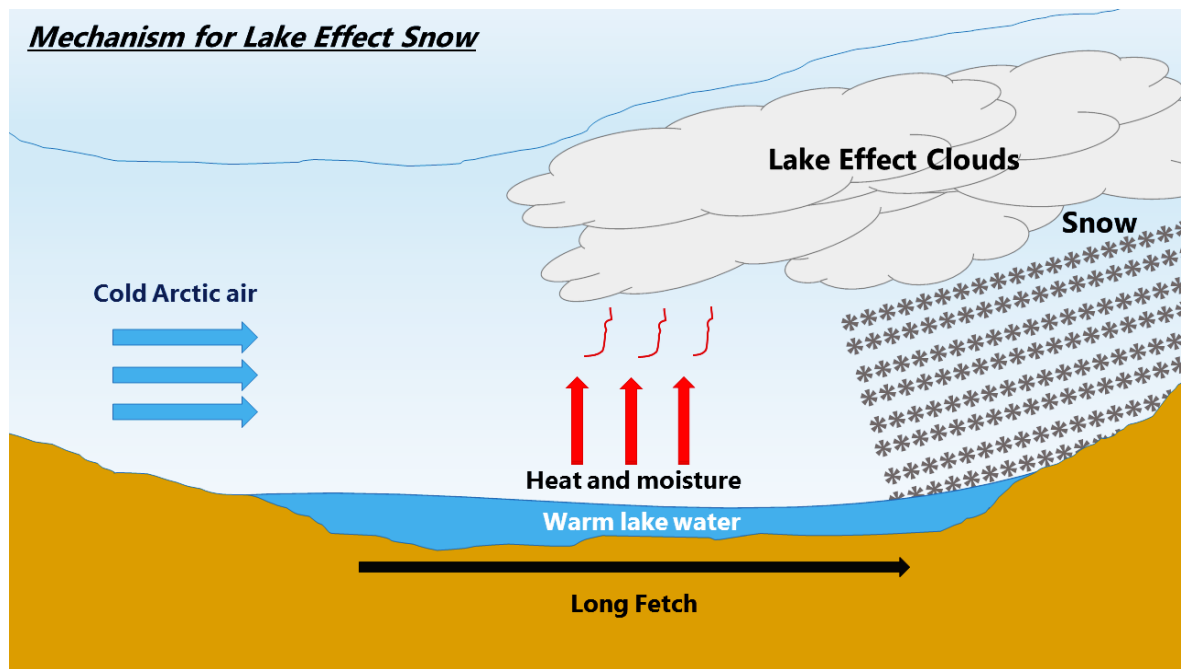


Figure 2.2. Formation mechanism for the Lake-effect snow meteorological event.

The FAA and NTSB recommend that certified airport operators include criteria for the type and depth of contamination and runway friction assessments that, when met, would trigger the immediate closure of the affected runway to aircraft operations in their snow and ice control plan (Milwaukee-General Mitchell International Airport 2015–16 Winter Operations Plan). Airport operations personnel are tasked with determining whether snow is dry, wet, or slush, along with its depth, to evaluate runway conditions. If any of the required conditions are met, the runway will remain closed until steps can be taken to remove any precipitation from it. The most widely used snow removal tactic is snow plows to move the snow into grassy areas nearby the runways. Sometimes, airport officials will try to impede any snow accumulation on runways by applying chemical treatments to them before the snow starts to fall. Only FAA, state, and locally approved chemicals can be used in either liquid or solid form; liquid chemicals include glycol-based fluids, potassium acetate base, and potassium formate-based fluids, while solids include sodium formate, and sodium acetate. The Milwaukee-General Mitchell International Airport 2015–16 Winter Operations Plan expresses that the efficient use of chemicals can significantly extend the operational usefulness of runways and taxiways during times of precipitation. Abrasives such as sand are also used when temperatures are near 0°C, as it provides a roughened surface on ice which can improve aircraft directional control and braking performance.

### *c. Wind*

Wind speed and direction at any location, particularly airports, can be affected by four parameters: surface roughness, geographical location, surrounding topography, and existing weather systems over the region. Runways are often built in such a way that the prevailing winds are favorable for planes to takeoff, land, or taxi without any complications (COMET Program

2017). Therefore wind blowing from an uncommon direction may result in changes in air traffic behavior. A wind of this nature is mostly considered a crosswind, which has a component directed perpendicular to the main heading of an exposed object (AMS Glossary 2017), such as a runway or an aircraft. Airplane takeoffs and landings in certain crosswind situations are very dangerous and are highly discouraged (FAA 2017), as these crosswinds could completely divert the plane, drifting it away from its intending direction of travel, and increasing the risk of veers during takeoff or landing. This aviation hazard could be further enhanced if any kind of precipitation is present on runways, or if aircraft brakes are not fully functioning.

One way to mitigate potential damage due to crosswinds is to build specific runways which are oriented perpendicular to the common mean wind flow, and create a viable option to takeoff or land in situations where wind direction on the main runway is not favorable. However, few airports have built such types of runways (Hord 2013), resulting in aircraft crew needing to manually maneuver most of the time if crosswinds are reported at an airport. The Flight Safety Foundation (FSF), along with the FAA, airplane manufacturers, and airlines have designed crosswind guidelines with recommended maximum crosswind speeds to let pilots know when it is safe to maneuver. These guidelines depend on the condition of the runway, as this is key for the pilot to be able to handle and manage the aircraft. If a severe winter storm causes ice to accumulate on runways, even a moderate crosswind could exceed the established limits and make a takeoff or landing unsafe (Elliott 2013). Table 2.4 presents a summary of these guidelines and limits, based on The Boeing Company's Crosswind Guidelines (Cashman 2016).

Table 2.4. The Boeing Company Guidelines and recommended maximum crosswinds during both takeoff and landing, adapted from Cashman (2016).		
<b>Runway Condition</b>	<b>Crosswind at Takeoff (knots)</b>	<b>Crosswind at Landing (knots)</b>
<b>Dry</b>	40	40
<b>Wet</b>	25	40
<b>Standing Water/Slush</b>	15	20
<b>Snow (dry)</b>	20	35
<b>Ice</b>	15	17

#### *d. Icing on Airplanes*

Ice on an aircraft, especially on its wings, can have a negative effect on its overall operation. According to Kulesa (2003), structural icing on wings and control surfaces increases aircraft weight, degrades lift, generates false instrument readings, and compromises control of the aircraft. Also, mechanical icing in carburetors, engine air intakes, and fuel cells impairs engine performance, leading to a reduction of power. Because of the hazards of ice on an aircraft, its wings are usually sprayed with a type of antifreeze before taking off during cold, inclement weather.

Aircraft icing is mainly produced by supercooled large drops (SLD), which are drops of water greater than fifty micrometers in a liquid state at temperatures below 0°C (Fernández-González et al. 2012). Such drops can freeze on aircraft structures that are unprotected or inadequately protected by anti-icing systems. Due to their larger size, SLD are not as likely as

small droplets to be carried around by wind, and given the velocity with which they fall, they would freeze upon contact (Politovich 2003). These large drops are often found within some stratiform cloud layers, with cloud tops usually at 10,000 feet or less, and air temperatures throughout the cloud layer remaining below 0°C, but warmer than -18°C (Vickens et al. 2000).

Studies on aircraft icing have been conducted, including one in Spain by Fernández-González et al. (2012), where flight plans were designed to collect scientific data from in-cloud systems capable of producing rainfall during winter. Flying into an icing environment to understand icing conditions that are not infrequent near the Madrid-Barajas International Airport was one the main objectives of this study. To achieve this, a research flight performed using a C-212-200 aircraft took place on 1 February 2012, taking off from a military base near the Barajas Airport. Several minutes after departing, and while flying at about 3,500 meters above the ground, the aircraft entered a region with a high SLD concentration and temperatures around -12°C, with liquid water content values in the range of 0.44 g m<sup>-3</sup>. This caused ice accumulation on the profile of the aircraft wings, and forced an early termination of the research flight. The authors concluded that the severe icing of this aircraft was likely due to the extremely low temperatures at 3,500 meters above the surface, the interaction of crosswinds with the region's topography in the creation of a mesoscale-low pressure center along the leeward side of the mountains, low ice nuclei concentration, and a weak thermal inversion at 600 millibars, which favored formation of vertical shear, leading to a more efficient collision-coalescence process. Based on their assessment, icing conditions could develop in very localized environments—such as airports—even when synoptic analysis may not indicate the potential for it.

De-icing of aircrafts and runways presents a challenge to both airlines and airports alike, as it is a deciding factor when cancelling or delaying flights. Since an aircraft icing accident on 22

March 1992 at the LaGuardia Airport in New York City, the FAA has improved their guidelines on de-icing procedures (Rasmussen et al. 2001). During this accident, 27 people lost their lives, 12 received serious injuries, and 9 received minor injuries when a plane from the airline USAir crashed just three seconds after taking off. The NTSB determined that the probable causes of this accident were the failure of the airline industry and the FAA to provide flight crews with procedures, requirements, and criteria compatible with departure delays in conditions conducive to airframe icing, and the decision by the flight crew to take off without positive assurance that the airplane's wings were free of ice accumulation after 35 minutes of exposure to precipitation following deicing. The ice contamination on the wings resulted in an aerodynamic stall, and loss of control after liftoff (NTSB 1993). Several other accidents involving ice have been reported, including one in 1994 when an ATR-72 crashed near Roselawn, Indiana, killing all 68 of its passengers and crew, while in 1997 an EMB-120 descending through icing conditions crashed on final approach to Detroit, Michigan, resulting in the death of 29 people (Bernstein et al. 2005).

## **2.4 Case Studies**

The impact of winter weather on flight operations in American airports has been studied in the past, with particular focus on the Northeast and the South. For instance, Schmidlin (1993) analyzed the impacts that several snowstorms had on civil activities, including airports, during December 1989 in the Lake Erie Snowbelt, the areas of Ohio, Pennsylvania, and New York that border Lake Erie and are prone to lake-effect snow. Data were gathered through surveys sent to key civil services, which included public school districts, universities, hospitals, electric utilities, and local airports. The region's largest airport, Erie International Airport in Erie, Pennsylvania, received 27.56 inches of snow, which was a monthly record. This airport closed several times

during the month due to snow, but none were longer than six hours. Cerruti and Decker (2011) studied the 9–11 February 2010 snowstorm that affected the Newark-Liberty International Airport in Newark, New Jersey. It started as a mix of rain and snow, but quickly changed to heavy snow and resulted in the closing of the airport for several hours.

Robinson (1989) conducted a study on weather-related delays and cancellations at the Atlanta Hartsfield International Airport using a three-year record, which featured various weather events that prompted flight cancellations, including snowfall. Although rare in Atlanta, snow can occasionally occur, leading to major disruptions in the city's airspace. Weather data were obtained from the Local Climatological Data Summaries produced by the then-named National Climatic Data Center (NCDC), now NCEI. Three major snowstorms were studied: 31 January 1977 [1], 20–21 January 1983 [2], and 24 March 1983 [3]. In [1], 15% of the flights for the day were canceled, most between 5:00 a.m. and 9:00 a.m. Eastern Standard Time. For [2], the storm started as snow but changed over to freezing rain, which prompted 65% of flights to be cancelled. Meanwhile, for [3], 47% of flights were cancelled, with the storm's precipitation falling as all snow.

Unlike other weather-related airport delays and cancellations, winter weather cancellations not only create problems in rescheduling both aircraft and passengers, but also for crew scheduling (Wykoff and Maister 1977; Robinson 1989). Robinson concluded that the number of delays and/or cancellations depends greatly on the time of storm arrival, as an arrival early in the day when few aircraft are operational allows for cancellations, whereas a late arrival prompts delays since operations at the airport are well under way.

Following a more aviation-oriented approach, Weber et al. (1991) constructed an Aviation Weather Delay Model (AWDM) to estimate flight delays due to weather conditions in 20 of the

major U.S. airports based on previous data. Similar to Robinson's study, data were also gathered from the NCDC database. One key difference between the two studies was the number of airports studied, and the fact that Weber et al. conducted their study for all four seasons instead of just winter. Only three weather categories were used in the study: thunderstorms, heavy fog, and reduced visibility. Their results presented reduced visibility (52%) as the year-round primary cause for flight delays, while thunderstorms and heavy fog were similar with proportions of delays at 25% and 23%, respectively.



### **CHAPTER 3: JOURNAL ARTICLE**

This chapter presents the methods used to conduct this study and the results obtained from it. Both are presented in the form of a complete, self-contained manuscript to be submitted to a scientific journal, which also includes a summary on the purpose of the study and the rationale to perform it.

**Meteorological Factors Affecting Airport Operations during the Winter Season in the  
Midwest**

manuscript submitted by:

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## **Abstract**

During the coldest months of the year, weather systems bring a variety of winter weather to most of the continental United States in the form of snow, sleet, freezing rain, which along with strong winds, low clouds, and reduced visibilities may create dangerous conditions. These weather conditions can result in major disruptions in air travel, leading to delays and cancellations of hundreds or thousands of flights, thus affecting the plans of millions of travelers. To assess the specific meteorological factors that prompt flight delays and cancellations in the Midwest region of the United States during wintertime, a comprehensive study was performed on nine of the largest airports (by passenger boardings) in the area.

Flight delay and cancellation data from eleven winter seasons (2005–06 to 2015–16) were collected from the Bureau of Transportation Statistics (BTS) and analyzed along with climatological data from the National Centers for Environmental Information (NCEI). A classification scheme was developed, and each flight was categorized according to the meteorological factor that could have prompted its delay. The results of the study revealed that visibility was the main meteorological factor affecting Midwestern airports, with low ceilings a close second. Blizzards were the main cause for flight cancellations.

### **3.1. Introduction**

Studies by the Federal Aviation Administration's (FAA's) Observation Network have shown that weather is the largest cause of air traffic delays in the National Airspace System (NAS), accounting for 69% of all air traffic delays from 2008 to 2013 (FAA 2017). The FAA defines a delayed flight as one in which an aircraft departs at least 15 minutes later than its originally scheduled time. Furthermore, the portion of delays due to weather represented nearly 10 million minutes in 2013. However, if weather conditions deteriorate to such an extent that it may become dangerous for planes to fly, flights could get cancelled instead of delayed. Winter is the season with the most cancellations due to weather; in fact, during the 2010–11 winter season, between 1 November and 11 February, a total of 86,000 flights were either delayed or canceled throughout the country Bureau of Transportation Statistics (BTS; 2017). During the cold season, weather systems bring snow, sleet, or freezing rain to most of the continental United States, excluding extreme southern areas of Florida, Arizona, and California due to their warmer and drier climates. Even southern cities such as Atlanta, Dallas, and Memphis have recorded some type of frozen precipitation, per climate records by the National Centers for Environmental Information (NCEI; 2017), but in lesser amounts than that experienced by more northern cities such as New York, Chicago, Minneapolis, or Buffalo. In this study, flight data were compared with hourly weather observations to determine the frequency by which different wintertime meteorological factors resulted in delays or cancellations of flights in major Midwestern airports.

Besides summer, winter is the year's busiest travel season, not only because it contains several holidays—including Hanukkah, Christmas, and New Year's Day—but also schools and universities are on winter break, which presents another travel opportunity. Further, the number of long-distance trips [defined as a destination at least 80 km (~50 miles) away] during the Christmas

and New Year's holiday period increases by 23 percent compared to the average number of long-distance trips during the remainder of the year (BTS 2017). Every year millions of Americans travel by plane either for business, leisure, or to visit family across the country. According to the BTS (2017), in 2015 there were 679 million enplaned domestic passengers. Although only 5 to 6 percent of holiday trips are by air, the frequency and strength of winter storms can seriously disrupt travel for passengers, airports, and airlines. This means that hundreds—and sometimes thousands—of flights are cancelled or delayed due to winter weather. In fact, in preparation for powerful winter storms, some airlines canceled flights before the actual storm arrived at the airport, which helped not only the airline, but also the airport itself, as it aided in the management process once the storm ended and regular operations resumed (Mouawad 2011).

In the northern hemisphere, meteorological winter extends from December through February. However, fluctuations in atmospheric patterns and geography may induce winter-like conditions as early as October or as late as April in some places. As temperatures turn colder, frozen precipitation becomes more common, leading to potential disruptions in daily life activities, including airport operations. For instance, Chin et al. (1997) interviewed different levels of aircraft-air traffic control (ATC) staff and pilots, who indicated that taxiing slows significantly when ground visibility is less than 0.8 km (0.5 mile), or when there is snow or ice on the surface. But during these times, there tends to be considerably less traffic due to precautionary flight cancellations by airlines. Several weather elements can impact airport operations during the winter, and are the main reasons why a flight is delayed or cancelled due to weather in the cold season (Table 3.1).

Table 3.1. Main factors affecting airport operations during winter.	
Factor/Reason	Impact on Flights
Cloud ceiling heights	Poor or no visibility of runways and or sky
Precipitation	Runway conditions—snow or ice
Wind direction and speed	Involuntary change of course of plane or it may not be able to safely takeoff or land
Icing	Accumulations of frost, snow, and/or freezing rain/drizzle on aircraft surfaces

Aside from snowfall produced by storm systems, some areas in the United States receive large amounts of frozen precipitation from the meteorological phenomenon known as lake-effect snow. It particularly affects the downwind areas of the North American Great Lakes during late fall and early winter (Wright et al. 2012), producing large amounts of snow during short periods of time in relatively small areas. In fact, for some locales near the Great Lakes, lake-effect snowfall accounts for almost half of their total winter precipitation (Scott and Huff 1996). Snowfall rates as high as 30 cm (~12 in.) h<sup>-1</sup> and 75 cm (~30 in.) day<sup>-1</sup> have been observed, as has lightning in some of the most intense cases (Markowski and Richardson 2011). The states of Indiana, Michigan, New York, Pennsylvania, and Ohio are the main areas in the United States that are affected by this phenomenon.

The impact of winter weather on flight operations in American airports has been studied in the past, with focus on the Northeast and the South. For instance, Schmidlin (1993) analyzed the impacts that several snowstorms had on civil activities, including airports, during December 1989

in the Lake Erie Snowbelt—the areas of Ohio, Pennsylvania, and New York that border Lake Erie and are prone to lake-effect snow. Data were gathered through surveys sent to key civil services, which included public school districts, universities, hospitals, electric utilities, and local airports. The region’s largest airport, Erie International Airport in Erie, Pennsylvania, received 70 cm (27.56 inches) of snow, which was a monthly record. This airport closed several times during the month due to snow, but none of the closings lasted longer than six hours. Cerruti and Decker (2011) studied the 9–11 February 2010 snowstorm that affected the Northeastern corridor. For instance, at the Newark-Liberty International Airport in Newark, New Jersey the storm started as a mix of rain and snow, but quickly changed to heavy snow, and resulted in the closing of the airport for several hours. Their results showed that when the variables of snow density and the timing and duration of the strongest winds and heaviest precipitation were combined with diverse degrees of societal susceptibility, it led to disparate impacts in several locations.

Robinson (1989) conducted a study on weather-related delays and cancellations at the Atlanta Hartsfield International Airport using a three-year record, which featured various weather events that prompted flight cancellations, including snowfall, which occurs from time to time, leading to major disruptions in the city’s airspace. Three major snowstorms were studied: 31 January 1977 [1], 20–21 January 1983 [2], and 24 March 1983 [3]. In [1], 15% of the flights for the day were canceled, most between 5:00 a.m. and 9:00 a.m. local time. During [2], the storm started as snow, but changed over to freezing rain, which prompted 65% of flights to be cancelled. Meanwhile, for [3], 47% of flights were cancelled, with the storm’s precipitation all falling as snow.

Unlike other weather-related airport delays and cancellations, those related to winter weather not only create problems in rescheduling both aircraft and passengers, but also in the

scheduling of crew (Wykoff and Maister 1977; Robinson 1989). Robinson (1989) concluded that the number of delays and cancellations depends greatly on the time of storm arrival, as an arrival early in the day when few aircraft are operational allows for cancellations, whereas a late arrival prompts delays since operations at the airport are well under way. Following a more aviation-oriented approach, Weber et al. (1991) were able to construct an Aviation Weather Delay Model (AWDM) to estimate flight delays due to weather conditions in 20 of the major U.S. airports based on previous data. One key difference between this study and that of Robinson was the number of airports studied, and the fact that Weber et al. conducted their study for all four seasons instead of just winter. Only three weather categories were used: thunderstorms, heavy fog, and reduced visibility. Their results presented reduced visibility (52%) as the primary year-round cause for flight delays, while thunderstorms and heavy fog were observed with similar frequencies, 25%, and 23%, respectively.

Given that New York City, with an estimated population of 8.5 million in 2015 (U.S. Census 2016), is the country's most populated city, and that major cities like Boston, Philadelphia, and Washington, D.C., lie along the northeastern region of the United States, past studies focused on flight delays and cancellations in airports located within this area; the majority classified the impacts of winter storms at large airports, and in the cities themselves. However, most of these studies focused solely on the impacts of a single storm on the Northeast's aviation system, and little research has been done outside of this geographical region. Likewise, there has been a lack of research into the meteorological factors that prompt disruptions in airport operations; flight delays and cancellations are impacts of a winter storm, and are used to measure how disruptive the storm is, but little is known about the specific weather conditions that caused the delays and cancellations.



The purpose of this study is to identify the meteorological factors that prompt flight delays and cancellations during the winter season in the Midwest region of the United States. To achieve this, flight delay and cancellation data, along with meteorological data for several of the Midwest's largest airports, were retrieved and analyzed. After assessing the weather conditions around the scheduled departure time, the meteorological factor(s) that prompted each flight's delay were determined. In the case of cancellations, broad synoptic-scale analyses were made to determine the type of system that prompted them.

### **3.2. Data and Methods**

#### *a. Study Area*

Much of the study of winter weather impacts in aviation has been made using major airports in the Northeast and Southern United States, but no significant study has focused on other regions of the country; the area selected for this study is the Midwest, which is defined by the U.S. Census Bureau as the area comprising the states of Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin, putting this region roughly between latitudes 36°N and 43°N, and longitudes 80°W and 104°W. The region's total population as of the 2010 Census was 66,972,390, accounting for 21.6% of the entire U.S. population. For this study, the Midwest was more narrowly defined as the area comprising the states of Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri, Ohio, and Wisconsin, as they represent 90.7% of the region's population, and are most likely to host the area's main airports.

The Midwest was also chosen because of the wide range of winter weather events experienced there, as it is in one of the main paths that strong low-pressure systems take during winter. Its relatively high latitudinal location makes it prone to experience longer durations of cold

weather, as cold air from the Arctic descends southward into the United States, effectively making the region one that receives all types of winter precipitation, prompting disruptions in all modes of travel. In fact, winter storms are the second-most frequent weather-related catastrophe in the region (Winkler et al. 2012).

Average winter temperatures from 1981–2010 for the Midwest range from  $-13^{\circ}\text{C}$  ( $\sim 9^{\circ}\text{F}$ ) in the far northern areas of Minnesota to around  $2^{\circ}\text{C}$  ( $\sim 35^{\circ}\text{F}$ ) in the southern sections near the Ohio River. The same trend is observed regarding snowfall, averaging less than 50 cm ( $\sim 20$  in) per year in the southern tip of Missouri, to more than 350 cm ( $\sim 138$  in) per year in the exposed northern parts of Michigan (Figure 3.1). The areas with the highest annual average snowfall are located on the leeward shores of the Great Lakes, due to the lake-effect snow events (Kunkel et al 2013).

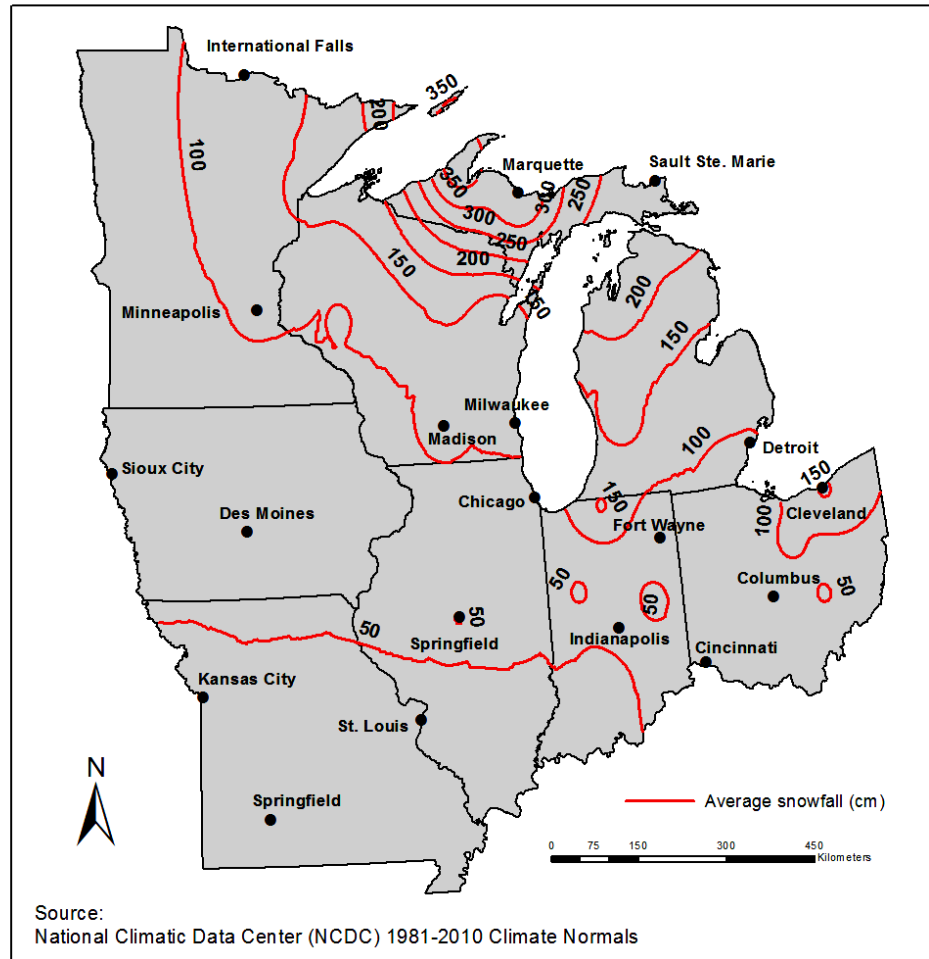


Figure 3.1. Average Snowfall in the Midwest (December–March). Major cities of the region are shown.

To select the airports to be studied, the FAA’s list of largest airports by passenger boardings in the United States for the 2014 calendar year was utilized. The list, which includes 550 airports, was narrowed down to the top 50 airports, and from those, the nine largest ones located in the Midwest were selected. As seen in Figure 3.2, every state included in the region’s geographical definition, except for Iowa, has at least one major airport; a comprehensive list of these airports is shown in Table 3.2.

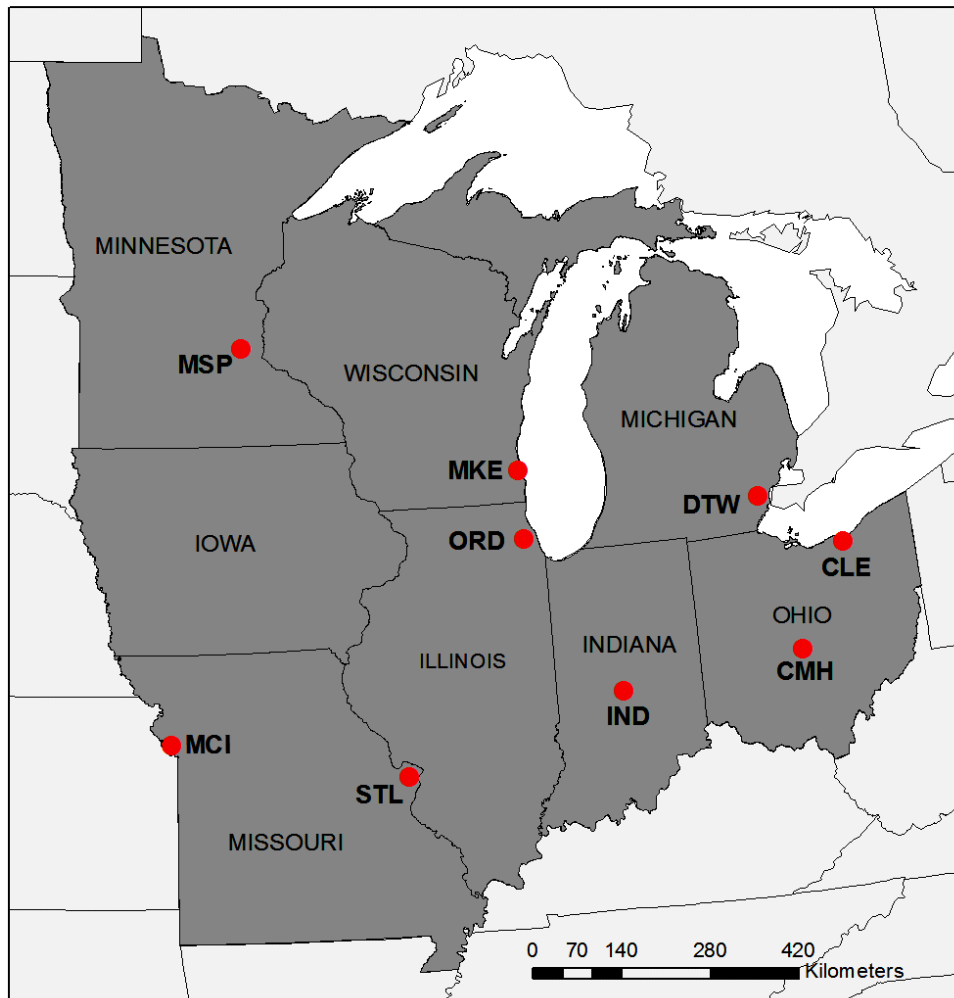


Figure 3.2. Study area along with the location of major airports in the Midwest region of the United States. Each airport is identified by its International Air Transport Association (IATA) airport code.

Table 3.2. Largest airports in the Midwest region of the United States by passenger boardings in 2014.						
<b>Study Rank</b>	<b>U.S. Rank</b>	<b>Airport Name</b>	<b>IATA airport code</b>	<b>City</b>	<b>State</b>	<b>Total Passenger Boardings</b>
1	3	O'Hare International Airport	ORD	Chicago	IL	33,843,426
2	16	Minneapolis-Saint Paul International Airport	MSP	Minneapolis	MN	16,972,678
3	17	Detroit Metropolitan Wayne County Airport	DTW	Detroit	MI	15,775,941
4	31	St. Louis Lambert International Airport	STL	St. Louis	MO	6,108,758
5	36	Kansas City International Airport	MCI	Kansas City	MO	4,982,722
6	47	Cleveland Hopkins International Airport	CLE	Cleveland	OH	3,686,315
7	48	Indianapolis International Airport	IND	Indianapolis	IN	3,605,908
8	49	General Mitchell International Airport	MKE	Milwaukee	WI	3,228,607
9	50	John Glenn Columbus International Airport	CMH	Columbus	OH	3,115,501

Chicago (the region's most-populated city), unsurprisingly, has the largest airport of the region, located 17 miles northwest of the city's downtown. To relieve O'Hare from being the sole airport in the city, the Midway International Airport, located about 10 miles west of downtown, serves as Chicago's secondary airport, handling around a third of the passengers of O'Hare. However, being in the same city, Midway also experiences its fair share of disruptions during extreme winter weather. Although Midway ranked as the 24th busiest airport in the United States, with 10,311,996 passenger boardings in 2014 (which would rank 4th on Table 3.2), its data were excluded from this study. The rationale behind this is the fact that O'Hare and Midway lie 15 miles away from each other, a small distance given the area's geography, landscape, and climate. If a weather system were affecting the Chicago area, both airports would likely be observing similar or nearly identical conditions, and by analyzing both airports, data overlapping could occur; therefore, only data from O'Hare were used.

#### *b. Data Collection*

In order to study the level of disruption that these airports experience due to winter weather, data on the amount of flights that were cancelled or delayed during eleven winter seasons (2005–06 through 2015–16) were collected from the BTS database. This database contains records pertaining to every kind of travel (air, land, sea) within the United States, including territories. Information that can be gathered from this database includes national transportation statistics, border crossing/entry data, airspace operations, and the National Household Travel Survey, among others. Data for this study were extracted from the national transportation statistics section of the database, specifically from the subject area of “Airlines and Airports.” Since this study is focused on delays and cancellations, data were extracted from the “On-Time Performance” sub-section,

which contains records of delayed and cancelled flights per month from all commercial airports that are regulated by the FAA. Flights are classified by their cause of delay, which follows the five categories that the Air Carrier On-Time Reporting Advisory Committee created in their 2002 assessment to the BTS: Air Carrier, Extreme Weather, National Aviation System, Late-arriving aircraft, and Security. As the goal of this study is to see which meteorological factors affect aviation during the winter season, flight data were taken from the *Extreme Weather* category. A set of new categories were created for this study, as BTS only classifies the cause of delay or cancellation as “Weather,” and does not specify what kind of weather prompted the disruption.

Although meteorological winter extends from 1 December to 28/29 February, winter conditions in areas of the Midwest can be experienced beginning around the middle of November and can continue well into the month of March; therefore, data were gathered from 15 November to 15 March for each year. As mentioned previously, the location of the region within the North American continent makes it prone to early and late-season cold episodes that sometimes are accompanied by high winter precipitation amounts. For this reason, the second half of November and the first half of March were included in the data analysis.

The National Weather Service (NWS) is the agency within the United States in charge of issuing watches and warnings in accordance with a specific set of criteria whenever a weather system has the potential to cause any level of disruption. NWS meteorologists use several tools such as satellite images, radars, and both upper-air and surface observations, among others, to forecast the potential impacts that any storm may produce in a specific area. One of those tools, surface observations, is taken by the Automated Surface Observing System (ASOS), which are weather stations that, for the most part, are located on the grounds of airports throughout the nation (NWS 2016), and are the primary source of real-time weather data in the aviation industry. Both

traffic controllers and pilots rely on ASOS data to make airplane-airport operation-related decisions such as takeoffs, landings, taxiing, and in extreme cases if weather conditions warrant, delaying or cancelling departing flights.

Climatological data in the form of the Monthly Climate Summary and the Daily Hourly Weather Observations from each airport's ASOS station were obtained from NCEI's Local Climatological Records database. The Monthly Climate Summary for a location contains weather statistics for each day of the month, including maximum and minimum temperature, maximum wind speed and gusts, and any significant weather that occurred during a single day. The Daily Hourly Weather Observations contain the standard hourly observations for every day of every month that was studied, along with special observations that the weather station reported outside of the standard observations. Special attention was given to the following parameters: surface temperature, surface dew point, surface winds (speed and direction), precipitation, cloud ceiling, and visibility. If for any reason any of these parameters was not available, the Iowa Environmental Mesonet archive of the aviation routine weather reports, better known as METARs (Meteorological Aerodrome Report), was used. METARs are usually issued hourly and serve as a description of the meteorological elements observed at an airport at a specific time.

### *c. Analysis Methods*

Data were filtered by selecting the flights that reported weather as their cause of delay, and sorted in descending order of the number of minutes each flight was delayed. Considering the FAA's definition of a delayed flight, delays of at least 15 minutes were selected first. However, since delays of this small magnitude are not likely to cause major disruptions, minimum connection times were looked at to further narrow the final sample for delayed flights into the most extreme



cases. It was found that minimum connecting times for domestic flights in large airports in the United States can be as low as 30 minutes in extreme cases, but usually less than 60 minutes (Perkins 2017), thus providing little room to afford any delays. By taking an average of this range, and considering the domino effect that a delayed connection may have on the national airspace, only flights with delay durations of at least 45 minutes were ultimately considered for inclusion. Given the great disparity in passenger boardings between the top three airports included in this study and the remaining six airports (Table 3.2; a difference of nearly 10 million passengers existed between DTW and MCI), two different approaches were taken to obtain a representative sample of data from each airport; they were divided into two categories: large airports and small airports. For large airports, the 35 days with the most delays were taken from each airport, while for small airports, the top 10% of days with delayed flights were used. This sampling process provided an adequate distribution of flights per airport, and avoided focusing too much on the three largest airports in the study region at the expense of the others.

After each delayed flight was sorted in descending order by the scheduled time of departure, NCEI's Hourly Weather Observations from each airport were assessed by looking at the weather parameters one hour before the scheduled departure time of each delayed flight to determine which meteorological factor(s) had the most influence in the decision to delay the flight. This determination was made using a classification scheme based on the FAA's factors for delaying flights (Table 3.3). The classification scheme for this study consists of eleven categories (factors), with criteria definitions that were derived from NWS, FAA, and ICAO guidelines, and adapted accordingly.

Table 3.3. The classification scheme used to determine the cause of flight delays or cancellations.	
<b>Meteorological Factor/Classification</b>	<b>Criteria</b>
<b>Low Ceiling</b>	Cloud base between 100 and 3000 feet above ground.
<b>Low Ceiling: Sky Obscured</b>	Sky obscured by either falling precipitation or by low clouds (Vertical Visibility reported).
<b>Visibility: Fog</b>	No precipitation reported. Visibility of 3 miles or less.
<b>Visibility: Snow</b>	Snow or Sleet reported. Visibility of 3 miles or less.
<b>Visibility: Blowing Snow</b>	Blowing Snow reported. Visibility of 3 miles or less.
<b>Snow on the runway</b>	Snow or Sleet reported, but does <u>not</u> cause visibility reductions of 3 miles or less, OR Snow/Sleet reported within 2 hours of scheduled departure, leading to possible accumulations in both taxiways and/or runways.
<b>Ice (Precipitation)</b>	Freezing rain/drizzle/ice pellets reported.
<b>Ice (Deicing)</b>	Temperatures at or below -18°C for 3 consecutive hours before scheduled departing time.
<b>Wind</b>	No precipitation reported. Sustained winds of 30 mph or greater OR gusting more than 38 mph.
<b>Thunderstorm</b>	Thunder reported and/or Cumulonimbus clouds observed.
<b>Combination of factors</b>	Any combination of two or more of the above factors being reported at the same time. Examples may include: Visibility of 1.5 miles caused by blowing snow AND winds gusting at 42 mph OR Visibility of 2.1 miles AND a ceiling of 800 feet

If the cause of a delay could not be determined from the available weather data, it was classified as “Unknown.” Examples of situations in this category include clear skies, light winds, and no obstructions to visibility. In some cases, fair weather was occurring at the departing airport, but inclement weather was occurring at other airports that may have affect the departure of planes headed to the departing airport; these cases are known as upstream delays and also fell under the “Unknown” category. An example of this may be that clear conditions were reported at IND, but a scheduled flight from IND to LAX (Los Angeles International Airport) was delayed due to weather. The plane covering this route flew from New York, having JFK-IND as its first leg, but because there was inclement weather in New York, the plane was not able to depart on time. The flight dataset used in this study did not specify the origin airport (in the example, JFK), so limitations existed in knowing from which airport the plane covering the main route (IND-LAX) came. Nevertheless, it was a delay in one of the airports studied, and would be counted as such, despite its cause remaining unknown. Once each flight was classified in one of these categories, a final tally was performed to determine which meteorological factor was most prevalent in influencing delays of flights during the winter season in nine of the major airports in the Midwest.

The selection process for the sample of cancelled flights was slightly different than for delays, since cancelled flights do not have any duration associated with them. Instead, flights were filtered by the number cancelled per day. It was found that the nine airports had a combined 1138 days with fewer than 75 cancelled flights per day, accounting for 85.1% of flights. Choosing to focus on the days when weather was most disruptive to air travel, only days with at least 300 combined cancellations between the airports were examined. Cancellations were also sorted by scheduled departure time and categorized by the type of storm that broadly affected airport operations (Table 3.4) using the Monthly Climate Summary for each airport from each month of

the sample. The determination of what type of storm affected each airport was done according to the overall weather conditions during the storm's duration.

Table 3.4. Types of storms that can cause flight cancellations. Definitions adapted from the NWS Glossary.	
<b>Storm</b>	<b>Definition</b>
<b>Blizzard</b>	The following conditions are expected to prevail for 3 hours or longer:  Sustained wind or frequent gusts to 35 miles an hour or greater; and  Considerable falling and/or blowing snow (i.e., reducing visibility frequently to less than a quarter of a mile)
<b>Ice</b>	Occasions when damaging accumulations of ice are expected during freezing rain situations. Significant accumulations of ice pull down trees and utility lines resulting in loss of power and communication. Significant ice accumulations are usually accumulations of a quarter of an inch or greater.
<b>Snow</b>	A low-pressure system that produces significant amounts of snow over a large region.
<b>Winter</b>	A low-pressure system that produces a combination of winter weather (snow, freezing rain, sleet, etc.) over a large region.

### 3.3. Results and Discussion

An analysis of the data was performed on nine airports in the Midwest over eleven winter seasons spanning from 2005–06 through 2015–16, where both flight delays and flight cancellations were assessed. However, these flight disruptions were approached in different ways, as specific weather factors leading up to delays could be extracted from an airport's climatological data, whereas cancellations were mostly produced by large, complex weather systems that affected entire regions, not only specific airports.

#### *a. Delays*

There was a total of 8399 delayed flights among all nine airports, and from those, 4771 flights (53.2%) had a weather-related delay of at least 45 minutes. The absolute number of delayed flights was used instead of percentages to observe a wider range of delays within the selected airports. As expected, Chicago's O'Hare International Airport had the largest share of delays from this subset, with 2956 (61.9%), as seen in Table 3.5. Each airport experienced at least one factor listed in Table 3, although the only one in which every factor alone contributed to delays was Detroit. Low visibility due to snow was the leading cause of flight delays, being the meteorological factor responsible for the delay of 1041 flights (Figure 3.3), accounting for approximately 21.8% of all delays. Following that, 688 flights (14.4%) were affected by ceilings that were severely reduced to the point that the sky was completely obscured and only vertical visibility was reported. The third most frequent reason for delays, ice, which required planes to undergo deicing measures, was responsible for the delay of 608 flights (12.7%). For its part, wind alone was the factor that contributed the least to the number of weather-related delays, with only 25 flights (0.52%) delayed.

However, wind was one of the factors that affected 91 of the 598 flights that were delayed due to a combination of factors, which was the fourth most common cause of delays.

Table 3.5. Number of delayed flights per factor in each studied airport.

<b>Factor</b>	<b>CLE</b>	<b>CMH</b>	<b>DTW</b>	<b>IND</b>	<b>MCI</b>	<b>MKE</b>	<b>MSP</b>	<b>ORD</b>	<b>STL</b>
<b>Low Ceiling</b>	15	1	126	11	13	12	52	281	12
<b>Low Ceiling: Sky Obscured</b>	2	9	91	19	11	18	79	448	11
<b>Visibility: Fog</b>	0	13	37	1	3	2	6	25	0
<b>Visibility: Snow</b>	35	20	101	5	7	37	99	712	31
<b>Visibility: Blowing Snow</b>	14	0	34	0	12	2	47	313	0
<b>Snow on the runway</b>	28	0	27	2	4	3	17	190	4
<b>Ice (Precipitation)</b>	0	33	78	5	12	0	30	177	16
<b>Ice (Deicing)</b>	7	9	45	0	0	2	50	491	4
<b>Wind</b>	0	0	18	0	0	0	0	1	6
<b>Thunderstorm</b>	9	0	29	0	6	13	0	0	0
<b>Combination of factors</b>	37	10	110	2	43	2	72	303	19
<b>Unknown</b>	0	0	33	0	0	0	37	15	5
<b>Total</b>	147	95	729	45	111	91	489	2956	108

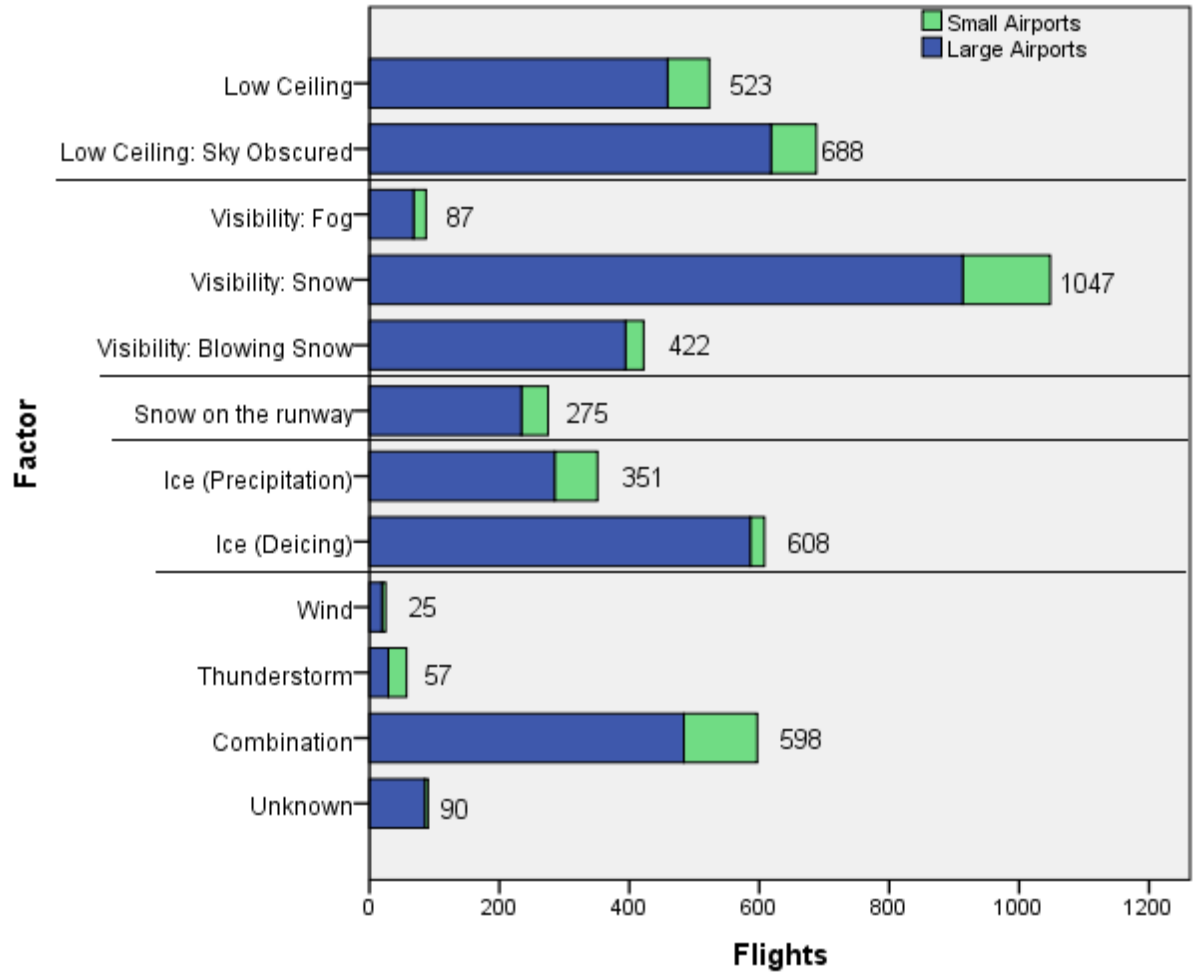


Figure 3.3. Number of delayed flights per meteorological factor in the studied airports. Blue denotes large airports, while light green denotes small airports. Numbers shown are totals for both large and small airports combined.

Winter storm systems have a “warm side,” which leads to precipitation falling as rain, and can even produce severe weather events in more southern locales, therefore a category for thunderstorms was included in the classification scheme. In all, 57 flights (1.1%) appeared to be delayed due to this factor, with almost three-quarters of them occurring in Detroit and Milwaukee. By looking at the temporal distribution of these thunderstorm-related delays, it was found that

Detroit's occurred in mid-March, which is expected, as this month marks the transition between winter and spring. On the other hand, Milwaukee's delays were rather surprising, as they occurred in mid-January, an unlikely time of year for this type of event, as the combination of less humid air and colder surface temperatures may prevent the formation of strong updrafts (NSSL 2017).

Flight delays were further analyzed by the number of days on which each factor was identified; if multiple factors caused delays at an airport on a certain day, it was counted as one day for each factor. In total, there were 408 days with delayed flights amongst all airports. As seen in Figure 3.4, low visibility due to snow was again the factor that affected the most flights, with 79 of the 408 days (19.3%) having at least one delay because of it. Following that, low ceilings accounted for 70 days (17.1%), and with 12.9% of days, a combination of factors was third most frequent.



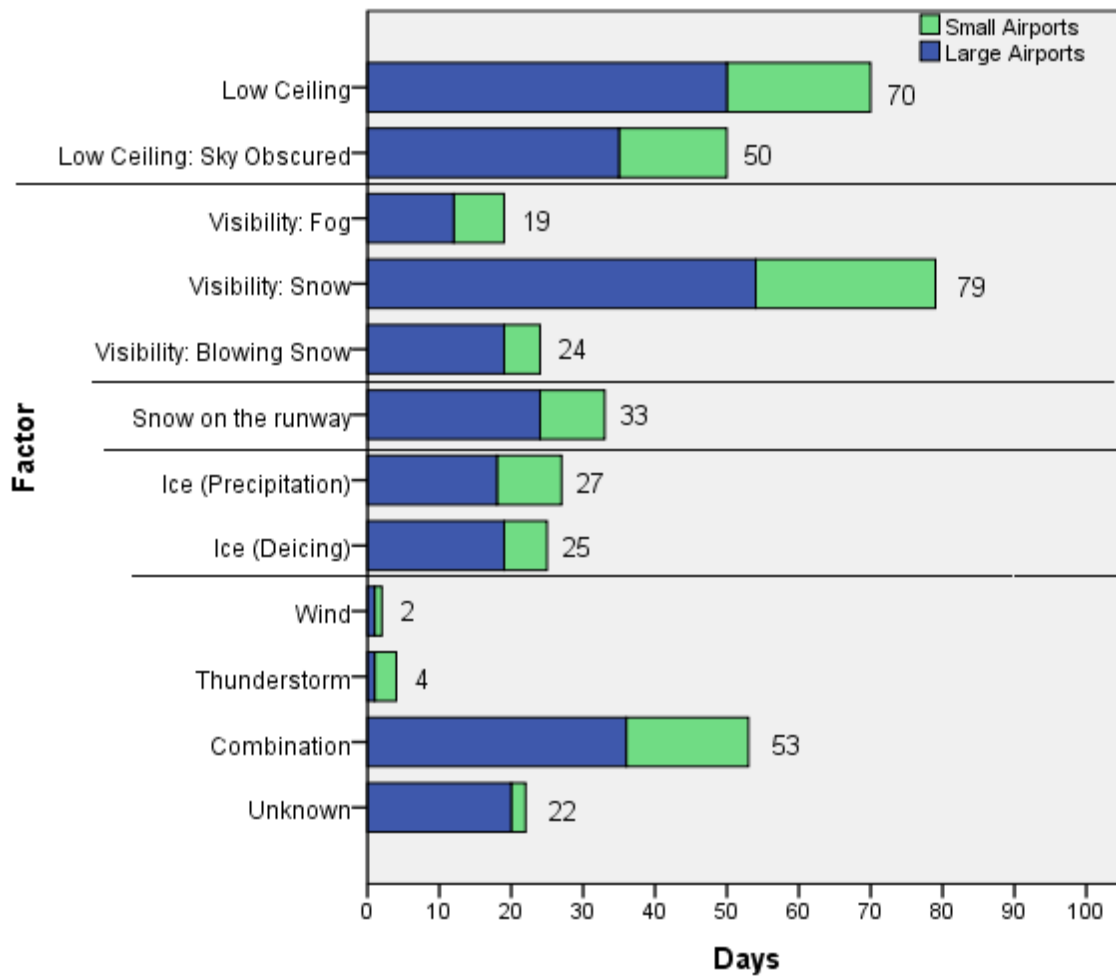


Figure 3.4. Number of days per meteorological factor in the studied airports. Conventions the same as Figure 3.3.

## 1) COMMON FACTORS

Based on the results described above, many delays were caused by two main factors: reductions in visibility due to snow, and low ceiling heights from either low clouds or obscured skies. Although visibility, low ceilings, and ice were expanded to two or more categories in previous analyses to provide more specific information about the causes of delays, it is instructive to examine these factors as a whole to identify overarching trends in flight delays. For the following analysis, the three subcategories relating to reduced visibility—fog, snow, and blowing snow—were consolidated into a single ‘visibility’ category, low ceilings due to clouds and obscured skies were combined into ‘low ceilings,’ and icy precipitation and deicing into ‘ice.’

It is seen in Figure 3.5a that these three consolidated factors account for more than 75% of delayed flights. Moreover, 58% of flights were delayed by either visibility or low ceilings, leaving these two factors as the primary causes for flight delays in Midwestern airports during the winter, with visibility (32%) delaying flights slightly more frequently than low ceilings (25%). The number of days with visibility and low ceilings were very close (Figure 3.5b), differing by only one percent. When airports were again grouped by size, similar frequencies were observed, with visibility and low ceilings resulting in the most delays. As shown in Figures 3.6a and 3.6b, large airports followed the overall proportion seen in all airports, while small airports (Figures 3.6c and 3.6d) experienced more visibility-related delays.

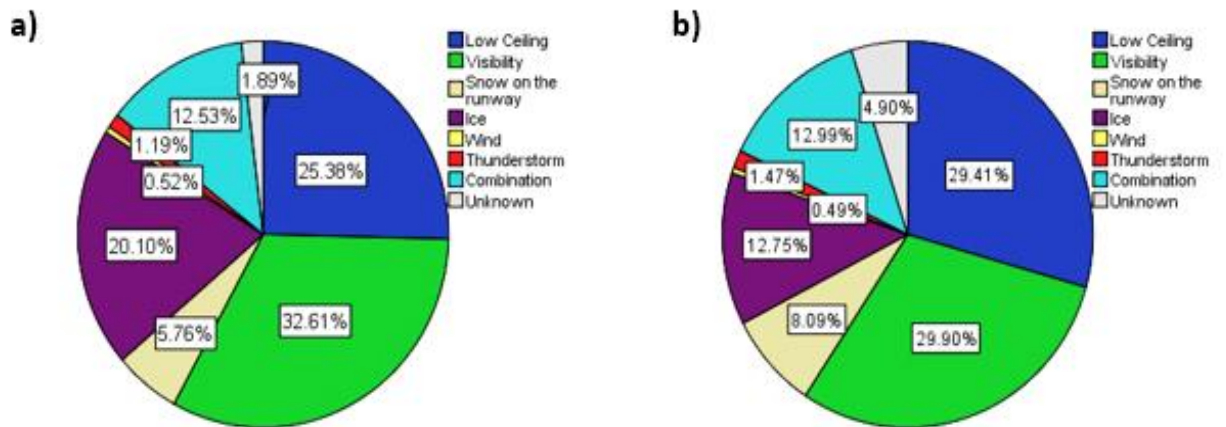


Figure 3.5. Combined factors for (a) number of flights per factor and (b) number of days per factor.

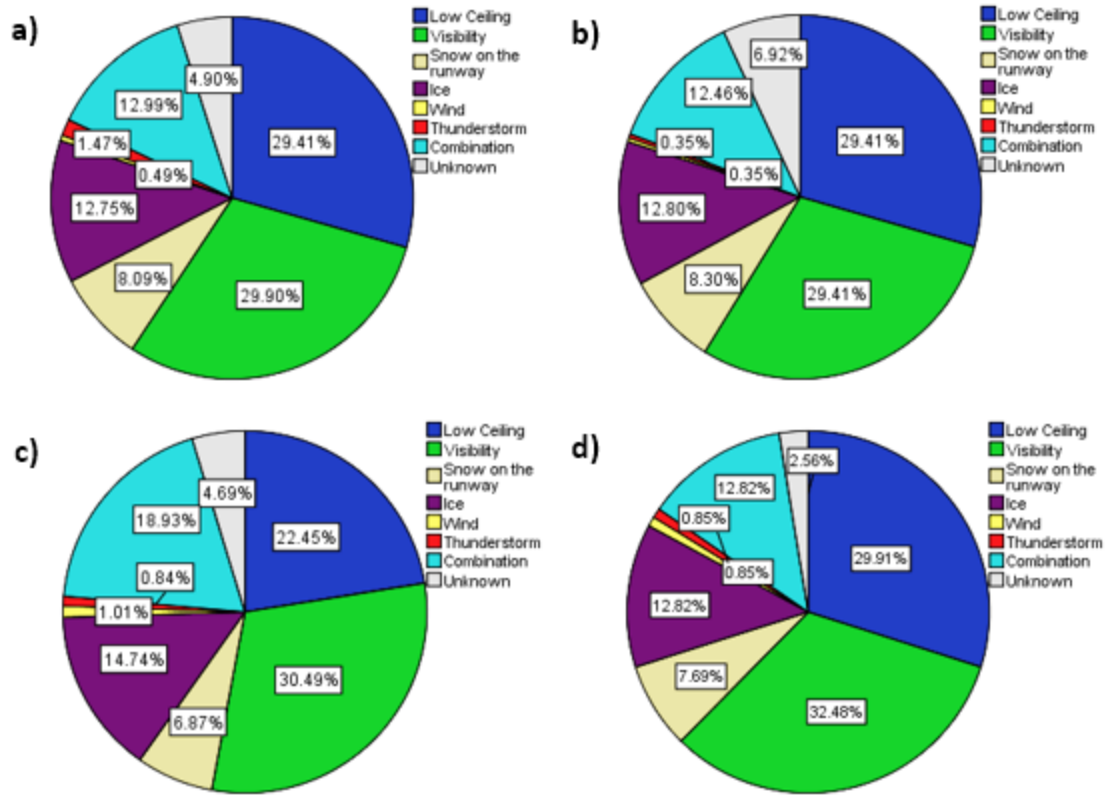


Figure 3.6. Combined number of flights and number of days per factor by airport size. Flight statistics for large airports is presented in (a), daily data for large airports in (b), flight statistics for small airports in (c), and daily data for small airports in (d).

It was shown that visibility and low ceilings were the main factors that affected airport operations in the Midwest during the winter season. As Roebber et al. (1998) found in their study, November through March had the highest percentage of hours per month with overcast conditions in comparison to the summer months in the city of Milwaukee, Wisconsin, based on climate averages calculated from 1961–90. Therefore, it can be said that given the high frequency of winter storms, the generally cold temperature pattern, and the relative low sun angle, winter is the season with the cloudiest days in the region, which affects both ceilings and visibility. Furthermore, according to Martin (2014) the frequency of the Instrument Meteorological Conditions in areas of

the Midwest, including Illinois, Indiana, and Ohio, exceeds 50% during the winter which indicates that low ceilings and visibility are often present in these areas. This finding by Martin is supported by the results of this study.

One way to assess the extent of disruptions due to a single factor, and to address the disparity between airport size, was to separate airports into two categories: large airports (DTW, MSP, and ORD) and small airports (CLE, CMH, IND, MCI, MKE, MSP, and STL). An in-depth analysis of both categories, along with the most common factors for delays, is presented in the following subsections.

## 2) LARGE AIRPORTS

Due to their size and status as hubs for major U.S. carriers, these large airports contributed most of the delayed flights with a total of 4174, which accounted for 87.4% of all delays in this study; the leading factor was low visibility due to snow with 912 flights (Figure 3.3), or 21.8%. Chicago had the most flights delayed due to low visibility from snow (712), with Minneapolis and Detroit having 99 and 101, respectively. Among these flights, reductions in visibility ranged from 0.125 miles (~0.19 km) to 3 miles (~4.8 km), with a median of 1.56 miles. The next most frequent factor leading to delayed flights with 618 (14.8%) were situations in which only vertical visibility was reported due to an obscured sky. Following that was plane deicing with 14.0% (586) of flights delayed. The factor that produced the least number of delays at these airports was wind, with only 19 flights (0.45%) meeting this classification. Low visibility due to snow and low ceilings were the two leading factors when considering the amount of days that had delays, with 18.6% and 17.3% of all days, respectively; these three airports had a combined 289 delay days (Figure 3.4).

*(i) O'Hare International Airport (Chicago, Illinois)*

Located in the Midwest's population epicenter, O'Hare International Airport is the largest airport of this group, and as such, it experienced the majority of delays. From the nearly 3000 disrupted flights reported at O'Hare, 24.0% were delayed due to poor visibility caused by snow falling on airport grounds, and falling precipitation or low clouds obscuring the sky was the second most common factor, with 15.1% of delayed flights (Figure 3.7a). Unique to this airport in this study, delays at O'Hare presented major disruptions in the entire U.S. airspace, resulting from its position as a major hub for many airlines in the country. These data reflect that status, revealing that departing flights to 153 domestic airports—including warm-weather destinations such as Miami, Honolulu, and San Juan—were delayed, the most for any airport in the study.

*(ii) Minneapolis-St. Paul International Airport (Minnesota)*

As the northernmost, and, on average, the snowiest of the nine airports studied, it is not surprising that reduced visibility due to snowfall was the leading meteorological factor at the Minneapolis-St. Paul International Airport, with 20.2% of delayed flights attributed to this factor (Figure 3.7b). Low ceilings due to obscured skies was the second most common factor affecting airplane departure, accounting for 16.1% of these data. A combination of factors was the third most frequent cause of delays with 14.7%.

*(iii) Detroit Metropolitan Wayne County Airport (Michigan)*

Michigan's primary airport was the only one in this study that experienced flight delays due to every factor (Table 3.2). All factors were nearly evenly distributed, however, as seen on Figure 3.7c, 17.2% of flights were delayed due to low clouds, making it the leading cause of

disruptions. There were at least five instances during each month in which half of the delayed flights encountered ceiling heights of 500 feet or less. A combination of factors and low visibility due to snow were second and third most frequent, accounting for 15.1% and 13.8% of flights, respectively. Detroit was also one of the airports that had delayed flights due to thunderstorm events near the airport, with 3.9% of its data categorized as such.

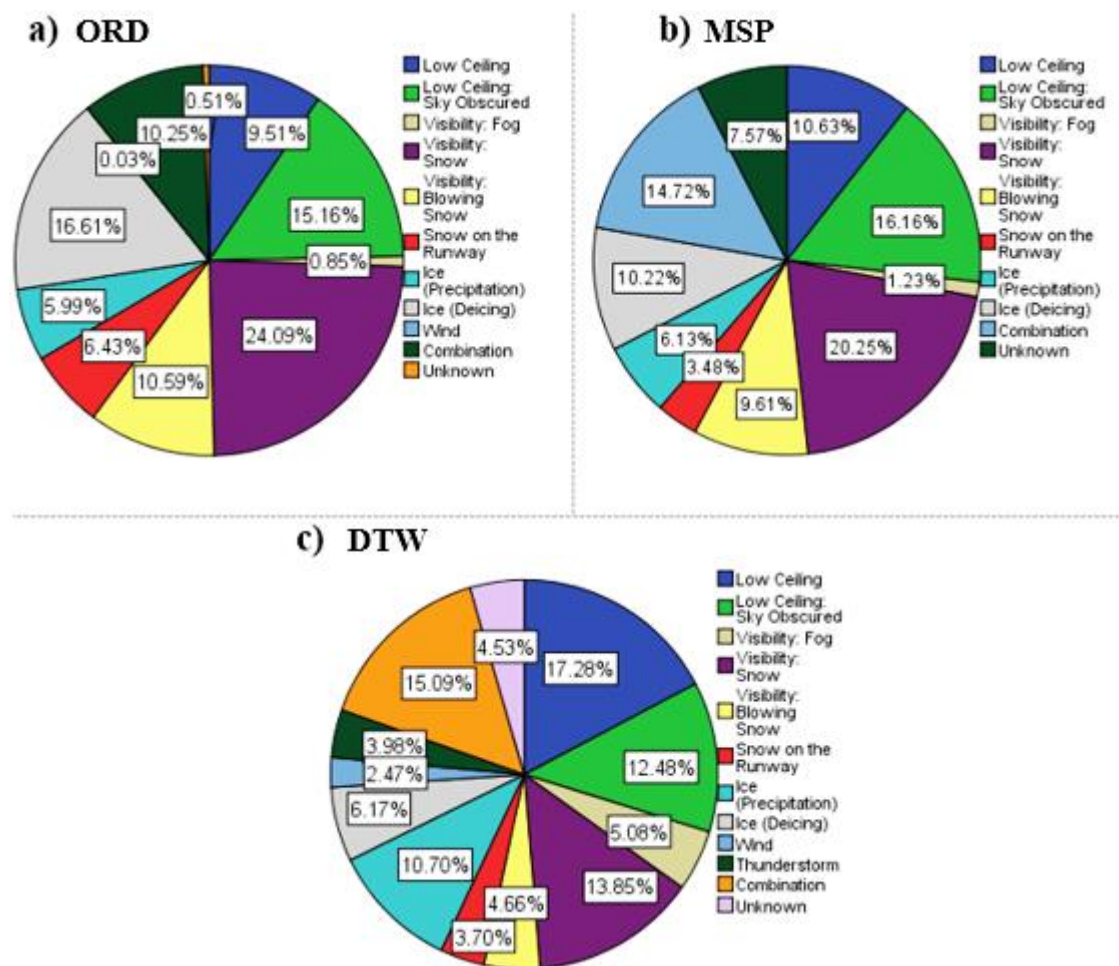


Figure 7. Delays per factor in each of the large airports in the study.

### 3) SMALL AIRPORTS

The other six airports accounted for the remaining 597 flights (12.6%) in the dataset, and despite having a significantly lower number of flights and passengers, these smaller airports also reflected the overall distribution of flight delays by factor, with low visibility due to snowfall as the main factor leading to delays (22.6%; Figure 3.3). Cleveland, Milwaukee, and St. Louis had 35, 37, and 31 flights delayed, respectively, in this category, the most among these six airports. Differing from the overall distribution, and the distribution associated with the three large airports, the next most frequent factor was a combination of individual factors that led to the delay of 113 flights (18.9%). All factors were represented in these combinations, with the most frequent including low visibility due to blowing snow (in several instances visibility was as low as zero miles), fog, strong winds, and icy precipitation. The two main factors at these airports, when looking at the number of days with delays in Figure 3.4, was low visibility due to snow (21.0%) and low ceiling (16.8%), of the 119 total days with delays.

#### *(i) St. Louis Lambert International Airport (Missouri)*

Although it is the southernmost airport in the study, St. Louis had 25% of its flights delayed due to snow, reducing visibility to three miles or less. Icy precipitation created problems for 16 flights (14.8%), while low ceilings alone accounted for 12 flights (11.1%) delayed. Combinations of either low visibility, low clouds, high winds, or fog was the second most common cause of delays at this airport (Figure 3.8a).



*(ii) Kansas City International Airport (Missouri)*

Kansas City was the second airport to have a large portion of its flights delayed due to a combination of factors, as it can be seen in Figure 3.8b, 38.7% of flights dealt with this issue. The main factors that contributed to these combinations were low ceiling, poor visibility due to snow, and freezing rain. There were six instances when flights were delayed due to thunderstorms, all of them on a single day: 27 December 2008 in the early morning hours. Temperatures were not especially warm, but the wind pattern in the area suggested a cold front was passing through, which likely initiated convection.

*(iii) Cleveland Hopkins International Airport (Ohio)*

Cleveland Hopkins International Airport is located nine miles southwest of the central business district of Cleveland, Ohio, and due to its proximity to Lake Erie, the airport's climate is greatly influenced. With respect to this study, lake-effect snow and strong winds were major factors that contributed to flight delays (Figure 3.8c). This airport was one of two that had a combination of factors as the main cause of flight delays, although low visibility due to snow was also a significant contributor. Main factors contributing to the 37 delays in Cleveland were high winds, blowing snow, and freezing fog.

*(iv) Indianapolis International Airport (Indiana)*

Located in the southwestern corner of the city of Indianapolis, this airport had the lowest number of delays of all the airports studied, with just 45 during the 10-year study period. About 42.2% of them were due to skies being obscured, impeding the horizontal view (Figure 3.8d). In all of these instances heavy snowfall was observed, and although snow was the primary reason for

the reduction in ceiling heights, an obscured sky was classified as a different factor since vertical visibility was treated as a ceiling measure rather than a visibility measure.

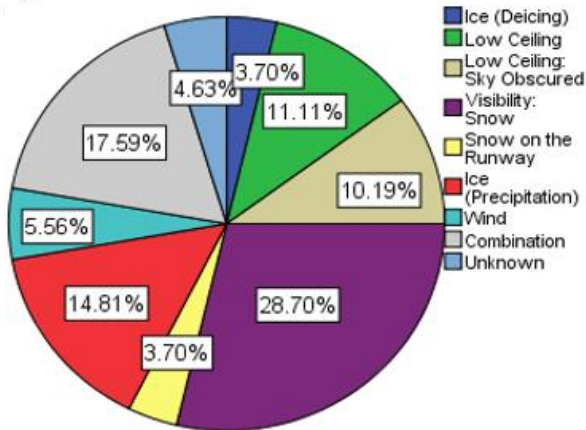
*(v) General Mitchell International Airport (Milwaukee, Wisconsin)*

Milwaukee's airport had about 40.6% of departures delayed due to snow reducing visibilities, and 19.7% due to instances where vertical visibility was an issue for planes as seen in Figure 3.8e. This airport, along with Kansas City, had flights delayed due to thunderstorms during a time of the year that isn't typically expected based on climatology. While only 13 flights were delayed due to thunderstorms, it is notable since this occurred in early January. Temperatures were just above 60°F prior to thunderstorm development on the day they occurred, which could have been a contributing factor.

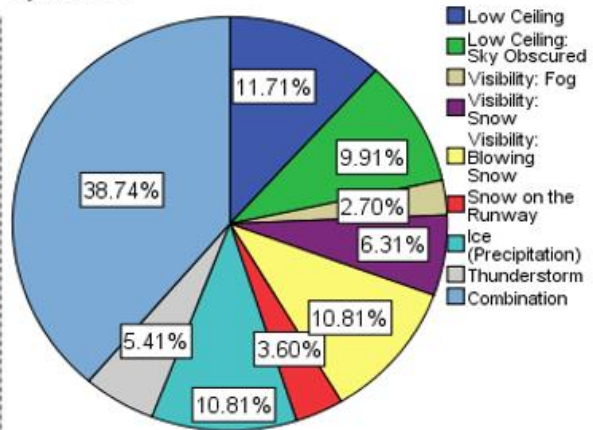
*(vi) John Glenn Columbus International Airport (Ohio)*

Due to its large distance from Lake Erie, this airport has a more continental climate compared to Cleveland, and it averages less annual snowfall. Therefore, is not surprising that icy precipitation in the form of freezing rain or ice pellets was the primary factor for delays at this airport, with 33 of the 95 flights having departed later than scheduled (Figure 3.8f). Low visibility due to snowfall was responsible for 20 delayed flights, making it the second most common factor at this airport.

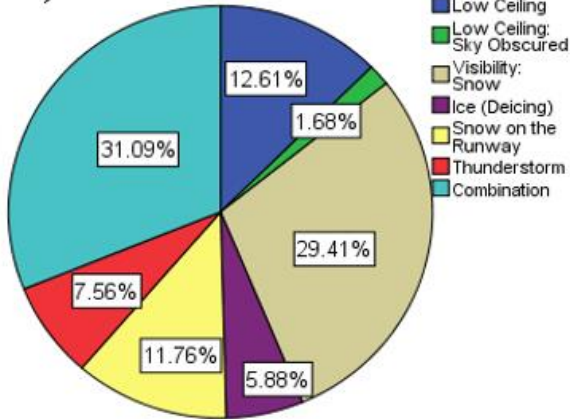
a) STL



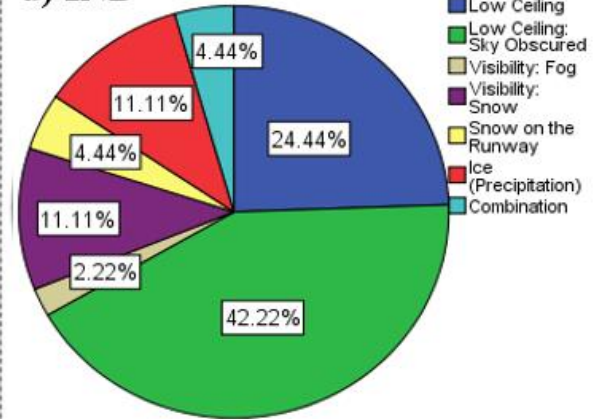
b) MCI



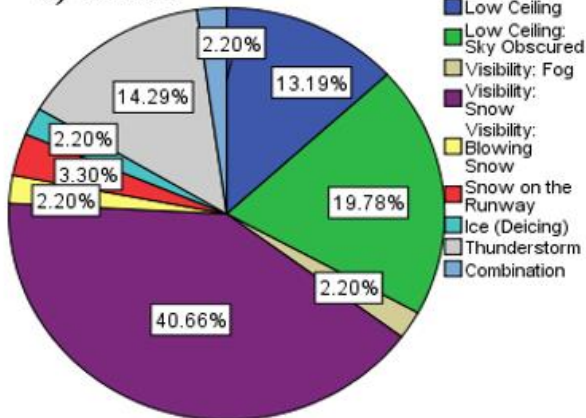
c) CLE



d) IND



e) MKE



f) CMH

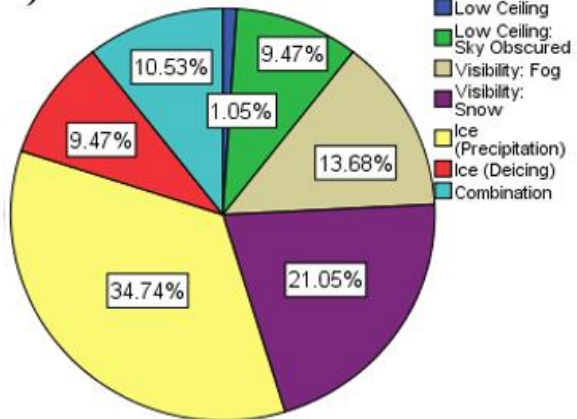


Figure 8. Delays per factor in each of the small airports in the study.

### *b. Cancellations*

During the study period, there were a total of 28 days with 300 or more cancellations, for a total of 15,512 weather-related cancellations throughout the nine Midwestern airports. As seen in Table 6, similar to delays, Chicago's O'Hare International Airport had the largest number of cancellations with 9,325, while Columbus International Airport had the fewest, with 437. Since O'Hare is clearly an outlier, the other eight airports were analyzed separately; cancellations average 773 per airport during the 28 days studied, and the average number of flights cancelled per day was 220. Detroit stands out as the airport with the most cancellations, while Columbus had the least. Indianapolis, which had the least number of delays during the period, was second to Columbus in cancellations.

When comparing cancellation frequencies by category, most were due to blizzards (55%; Figure 3.9), while snowstorms accounted for a significant proportion (31%) as well. Of the 28 days that saw at least 300 cancelled flights across all airports, 13 had blizzard conditions (Figure 3.10), which relates to the high number of individual flights that were canceled. From an airport operation perspective, blizzard conditions are particularly dangerous for any flight, as they represent possible reductions to visibility, heavy snow, and strong winds, while crosswinds may also be present.

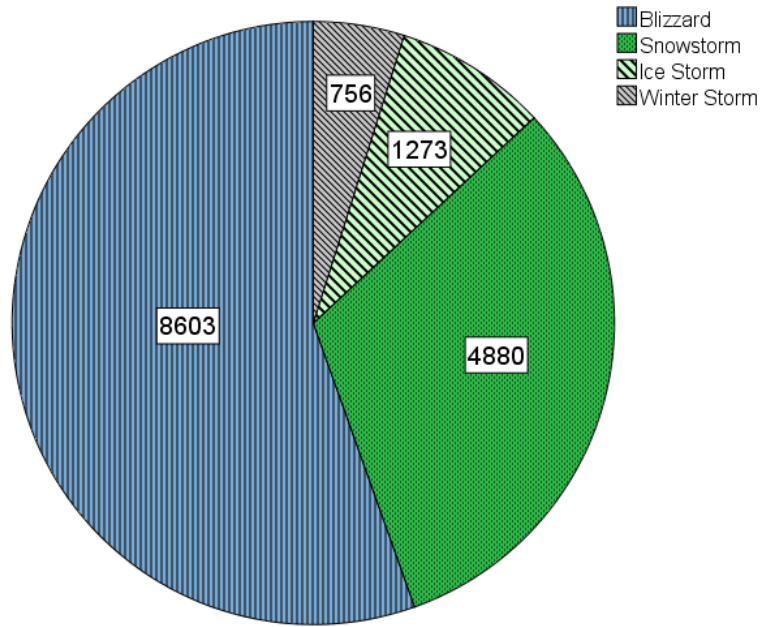


Figure 3.9. Number of cancellations per storm type.

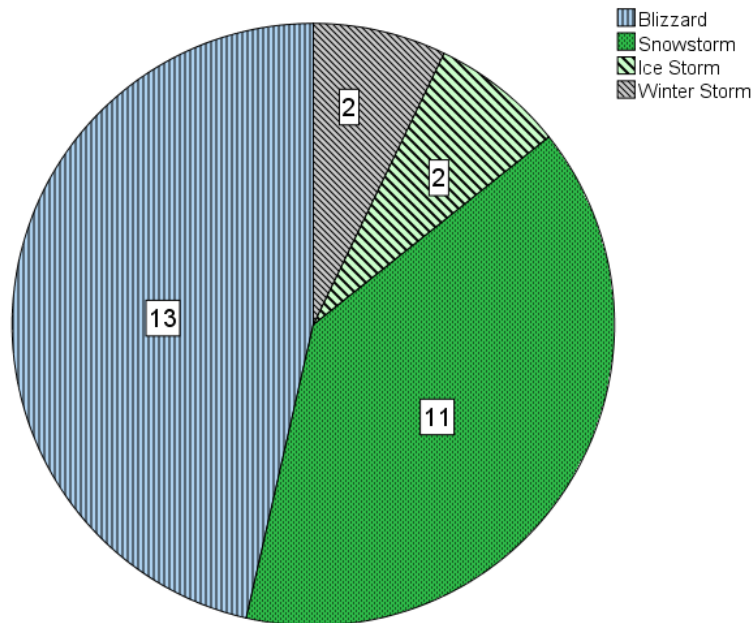


Figure 3.10. Days of cancellation per storm type.

### **3.4. Conclusions**

The purpose of this study was to identify the meteorological factors that prompt flight delays and cancellations during the winter season in the Midwest region of the United States. Due to the high latitude of the area, winter conditions in the Midwest may extend from mid-November to mid-March, bringing high amounts of wintry precipitation, strong winds, and extended periods of cloudiness and cold temperatures. Aviation is one of the first areas affected by these hazards, prompting the delay or cancellation of flights. In order to discover the exact causes of flight delays and cancellations, data from 11 winter seasons (2005–06 to 2015–16) were analyzed to determine the meteorological factors that most affected airport operations in the Midwest. Since winter weather conditions may be experienced both very early and very late in the season, the period from 15 November to 15 March was selected to conduct the study. Data were collected from several sources such as the Bureau of Transportation Statistics, Federal Aviation Administration, National Centers for Environmental Information and the Iowa Environmental Mesonet.

Airport selection was performed using a list of the largest airports by passenger boardings in the nation; nine airports in the region were selected. All states in the area, except for one, had at least one airport in the final sample. Due to the large disparity between their sizes, airports were further divided into two categories, large and small. For delays, large airports had a sample that consisted of the 35 days with the most delays from each airport, while for small airports the top 10% of delayed flights per day were used. Finally, to correctly assess meteorological data, delays and cancellations were analyzed differently.

Results revealed that visibility reductions of 3 miles or less due to snowfall was the meteorological factor that caused the most delays among the nine airports studied. When joining all low visibility and low ceilings categories into one, low ceilings and visibility are the two main

factors that affected airport operations in the Midwest during the winter season. Likewise, low visibility was the factor with most delay days. Although there was a marked difference between airport sizes, both large and small airports shared the overall distribution of flights delayed by factor, with low visibility due to snowfall as the main factor for delays. Based on an examination of the snowfall climatology of the area, it is not surprising that this type of winter precipitation was the cause for lower visibilities in the region. Blizzards were the most common cause for cancellations, with more than half of all canceled flights the result of this type of weather event. Likewise, the most days with cancellations occurred during blizzard conditions. By being the most hazardous weather event in the cancellation categories, blizzards were the most likely to affect the most flights in the area.

The choice of the study period (15 November to 15 March) was effective in not only capturing the entirety of winter-weather-related delays, and thus providing enough data to conduct the study, but also capturing a variety of disruptive weather events, including thunderstorms, which are not common during the colder months. Dividing airports by size proved to be very useful, as not all airports handle the same quantity of flights and passengers, and if left all grouped in one single group, results would have been biased towards the largest airport, in this case, Chicago. If this were the case, this study would have neglected the region's smaller airports, and the purpose of the study would not have been achieved.

This study could serve as a guideline for potential travelers, airlines, and airports, who may use it to better understand weather conditions surrounding winter in the Midwest, and how to foresee possible delays due to low visibilities. Winter weather researchers could also benefit from this study as it may serve as a climatological record for the area, and as proof of how strong winter storms can affect a society's day-to-day activities. The study may be extended by focusing on those

Midwestern airports which rank 51–100 on the FAA’s list, which may provide a better insight into the operational impact winter weather has on smaller airports. Other future work may include focusing exclusively on specific holidays such as Thanksgiving and Christmas, which are dates when airports experience a significant rise in the number of travelers.

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## CHAPTER 4: CASE STUDIES

To better appreciate airport disruptions due to delays and cancellations in the region, two case studies were conducted. The first focused on an event with delays due to lake-effect snow, and the second explored a winter storm event that resulted in the most cancellations at the airports in the effected region.

### 4.1. Case 1: 20–21 January 2014 Chicago, Illinois Lake-Effect Snow Event

Chicago, Illinois, located on the southern shores of Lake Michigan, receives approximately 45 inches of snow per year, mostly due to low-pressure systems and cold fronts that pass through the area. Due to the prevailing west-to-northwest winds, the city rarely experiences lake-effect snow. However, during the late hours of 20 January and early 21 January 2014, a shift in wind direction, sufficient moisture, and below-freezing temperatures resulted in the development of a narrow snow band over the lake that reached the Chicago metropolitan area. This band resulted in accumulations of between five and eight inches of snow and led to various flight delays and cancellations at both of the city's airports.

#### *a. Climatology and background*

This lake-effect snow event occurred in the month of January, the time of year when Chicago experiences its snowiest month, with an average of 10.8 inches (NCEI 2017). However, January 2014 had already surpassed this amount by 19 January, with a total accumulation of 23.8 inches. Furthermore, the total snowfall received since 1 December 2013 was 38.0 inches, making this the third snowiest 1 December 2013 through 19 January 2014 period on record. Since the

city's official weather-reporting station is located at O'Hare International Airport, most observations refer to this station; it's located about 16 miles northwest of the city center. Chicago Midway International Airport is used as a secondary weather station, and is located closer to the downtown area.

Data were collected from NWS Chicago records; daily and hourly weather data were obtained from the NCEI. Radar images were obtained from the Iowa Environmental Mesonet Radar Products Archive. As the NWS Chicago office does not perform radiosonde launches, a model sounding for O'Hare Airport obtained from the Iowa Environmental Mesonet BUFRKIT Archives was analyzed. To determine the synoptic setup for the event, surface and upper air maps were also retrieved from Plymouth State Weather Center's Archives. Flight delay and cancellation numbers were taken from the Bureau of Transportation Statistics On-Time Performance Data.

#### *b. Synoptic setup*

The 1200 UTC NAM4km model sounding on 20 January for O'Hare Airport (Figure 4.1) depicted a somewhat cold atmosphere, with surface temperatures near  $-2^{\circ}\text{C}$ ; the entire temperature profile remained below  $0^{\circ}\text{C}$ . Temperature and dew point lines were very close to each other, suggesting saturation, and possible precipitation. Figure 4.2 presents the surface pressure contour analysis at 1200 UTC, which depicts a low pressure in northern Wisconsin. The closest airport to the low of the ones studied was Milwaukee which reported light snow, a temperature of  $-6^{\circ}\text{C}$  and a north-northeast wind. Meanwhile, the surface observations from O'Hare Airport in Chicago agreed with the model sounding as the station was reporting overcast skies,  $0^{\circ}\text{C}$ , and a light north wind. Milwaukee's observations were indicators of what was coming to the Chicago area.

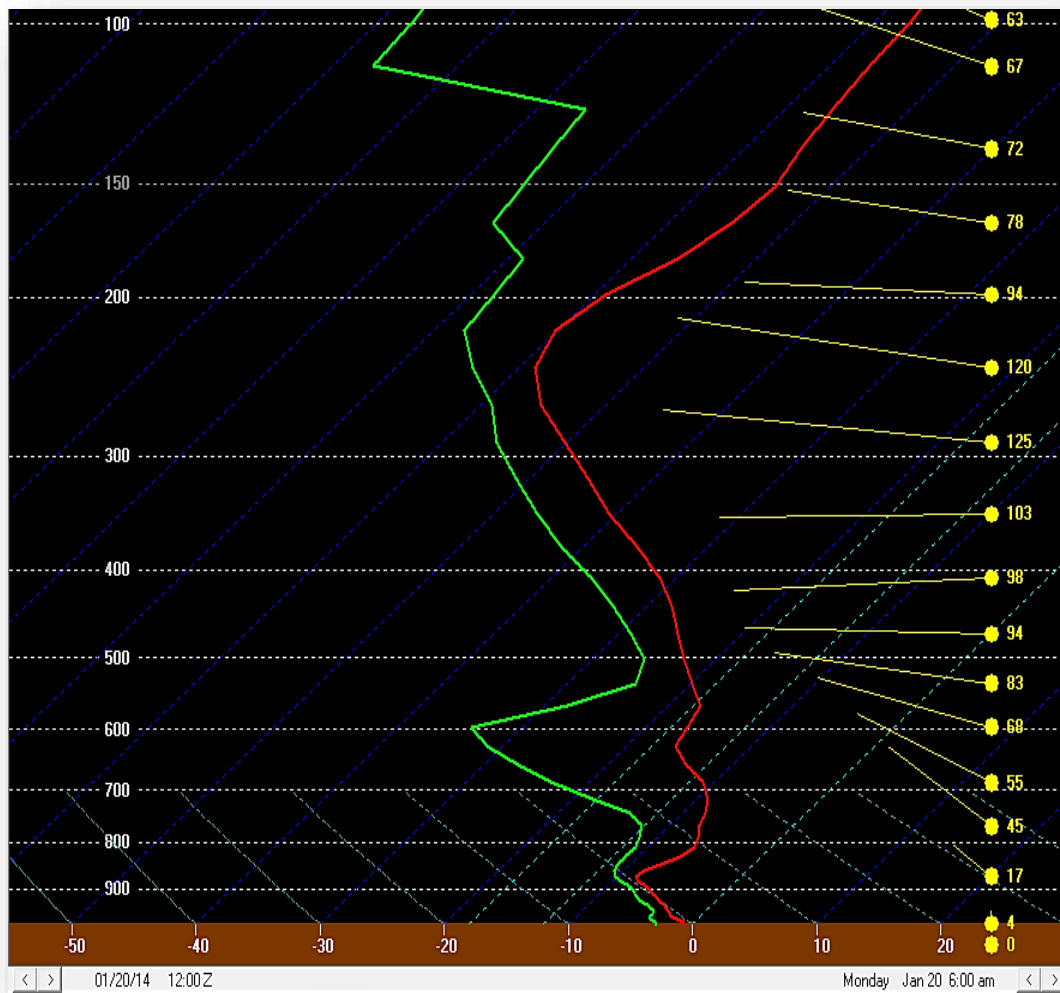


Figure 4.1. NAM4km model sounding for ORD on 20 January 2014 at 1200 UTC. The red line denotes environmental temperature, while the green line denotes environmental dew point. (Iowa Environmental Mesonet's BUFKIT Archives 2014).

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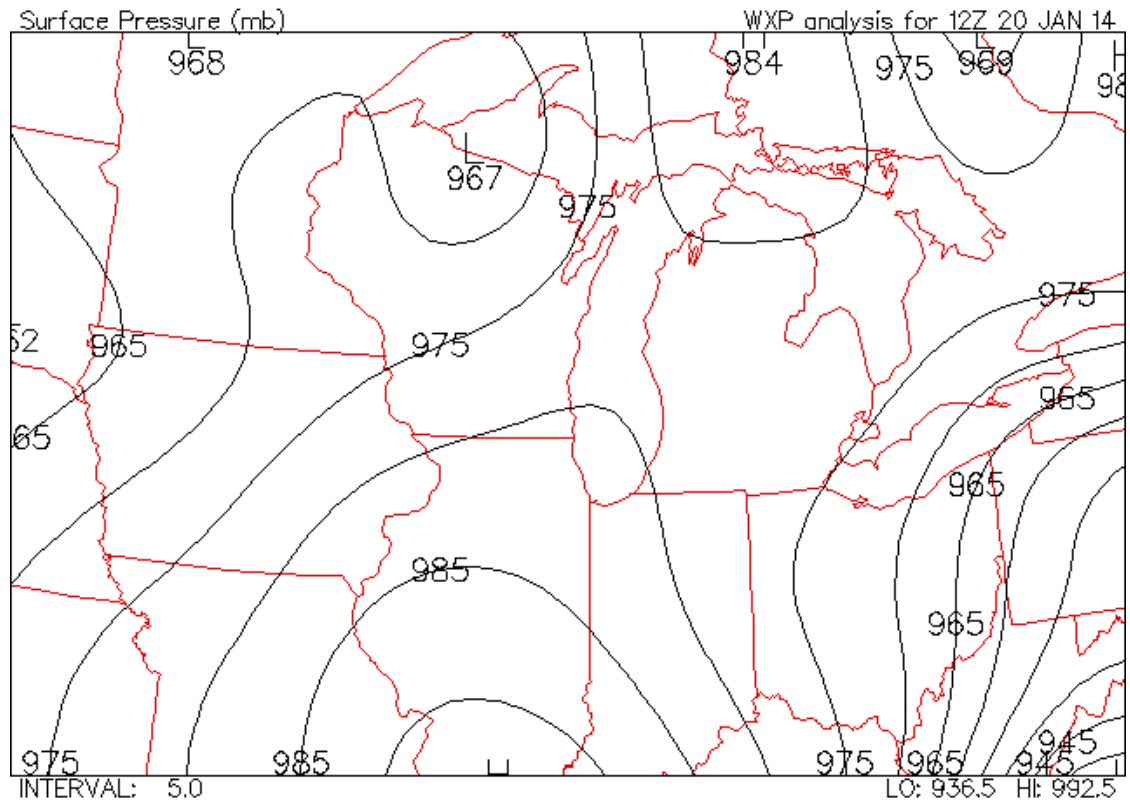


Figure 4.2. Surface Pressure contour analysis map for 20 January 2014 at 1200 UTC. (Plymouth State University Weather Center Surface Maps Archive 2014).

A cold front associated with the low passed through Chicago between 1300 and 1600 UTC, bringing very cold air; by 1900 UTC surface temperatures in Chicago dropped to  $-3^{\circ}\text{C}$ . Precipitation associated with this front did not start falling until several hours later. As the cold air mass moved southward, it also crossed over Lake Michigan, providing a key ingredient in the development of the lake-effect snow event that would occur hours later: arctic air. Although the water close to Chicago was between 40% to 90% frozen, the overall extent of ice covering Lake Michigan was below 10% at that time, while the temperature of its water near the surface was around  $1.8^{\circ}\text{C}$  (Figure 4.3), effectively putting it above freezing.

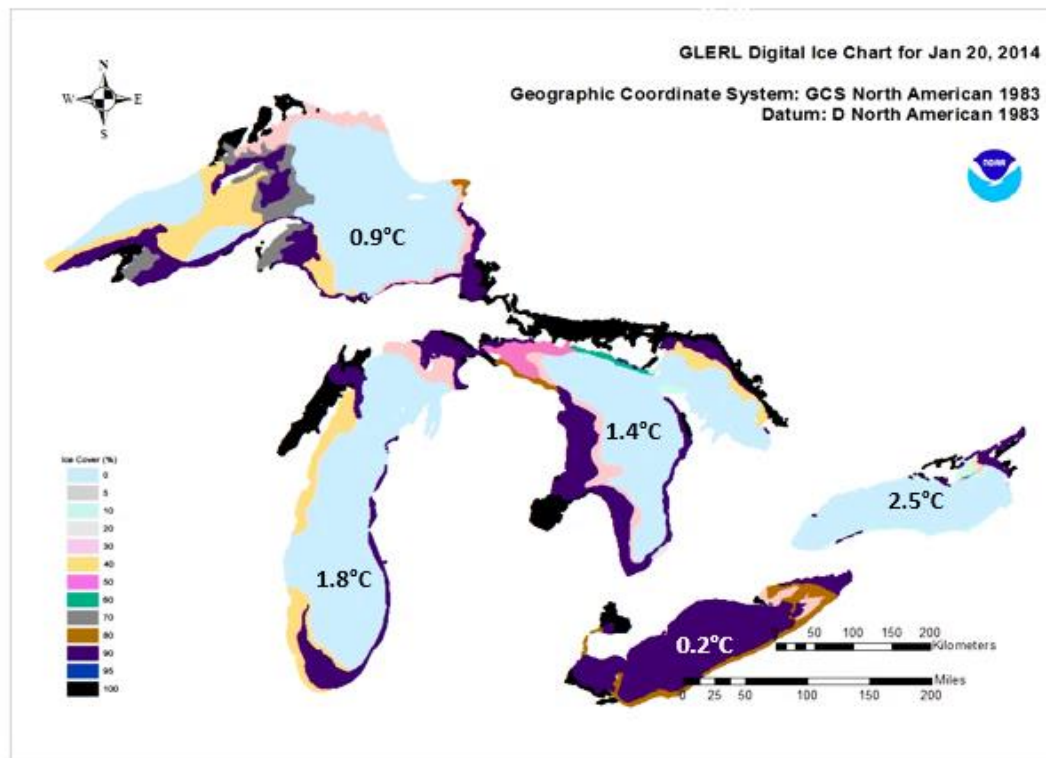
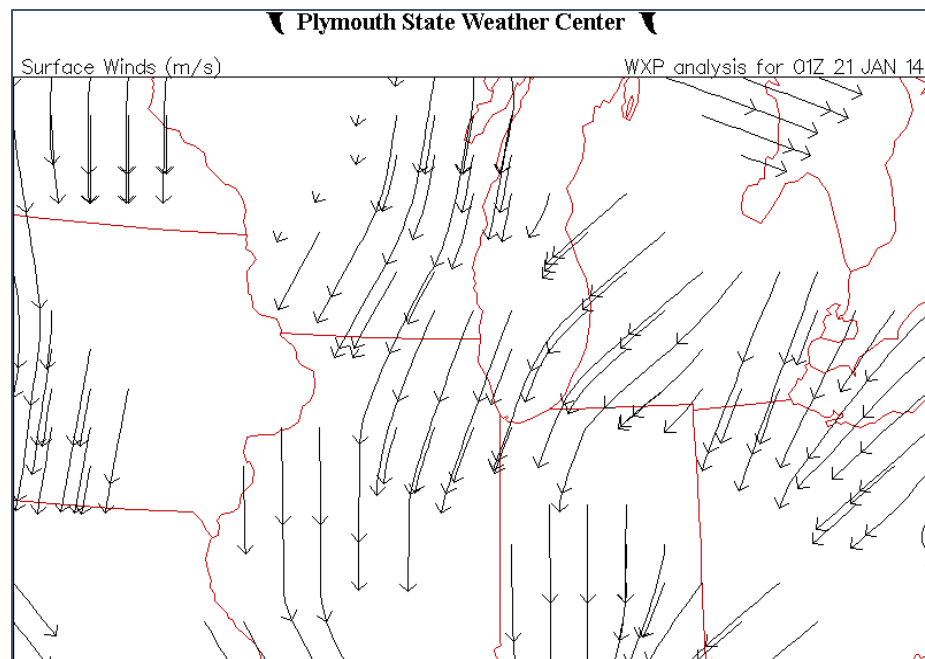


Figure 4.3. Water temperature and percentage ice cover of the Great Lakes on 20 January 2014 (Great Lakes Environment Research Laboratory Archives 2014).

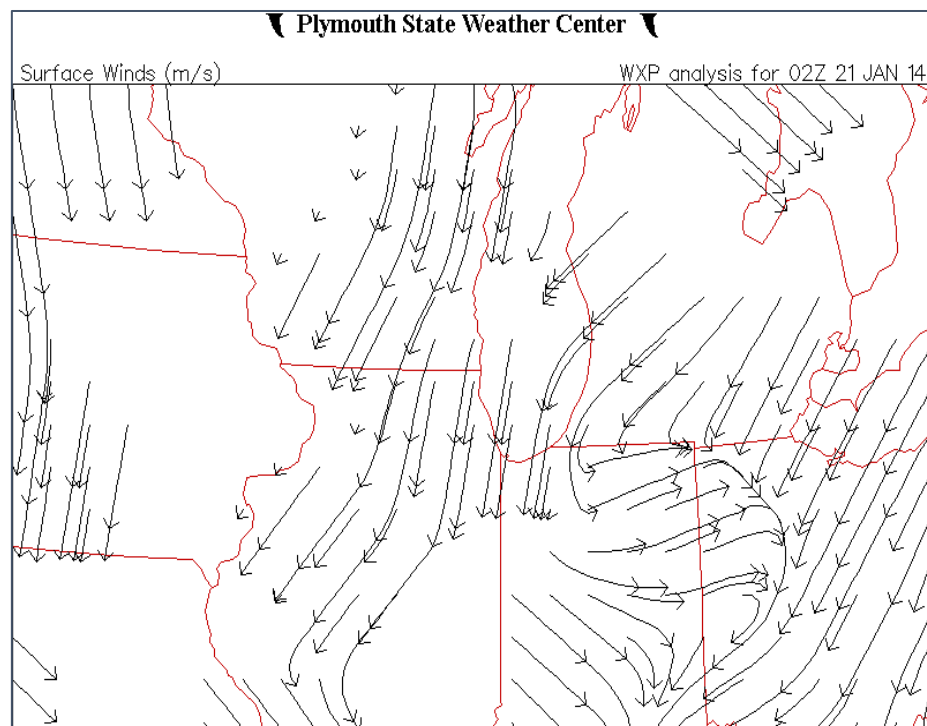


*c. The lake-effect snow event*

At 2300 UTC, precipitation associated with the low-pressure system began to fall in the area, with both of Chicago's airports reporting snow at that time, along with a light northeasterly wind. By 0100 UTC on 21 January, most of the snowfall associated with the low-pressure system and associated cold front moved southeast into Indiana, although some light snow was still being reported in Chicago. From surface observations, it was seen that between 0100 and 0200 UTC, there was a direction change to a more northerly wind in the Chicago area (Figure 4.4), in part due to a high-pressure system that moved into northeastern Wisconsin. Surface temperatures fell to around -6°C, and radar imagery showed a break in the snowfall.



(a)

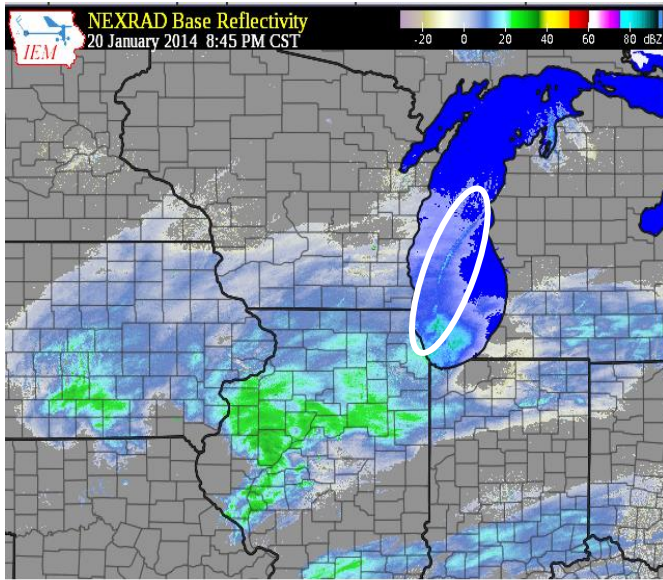


(b)

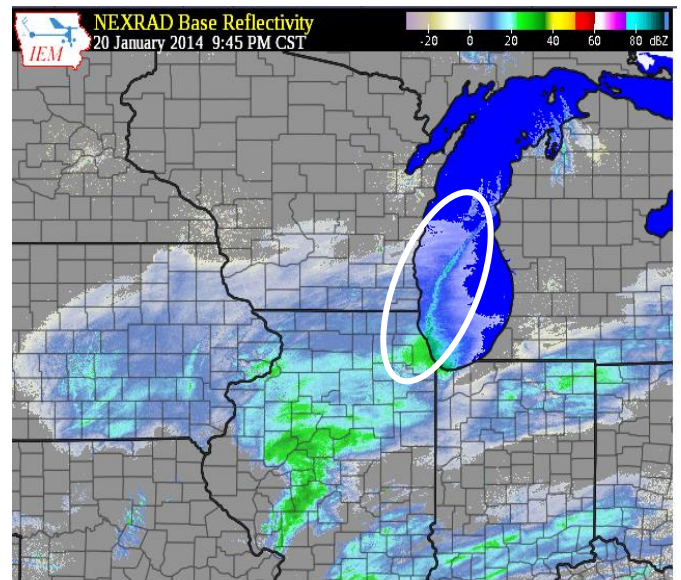
Figure 4.4. Surface Wind Streamlines for 21 January 2014 at 0100 UTC (a) and 0200 UTC (b) (Plymouth State University Weather Center 2014).

Furthermore, the same radar imagery showed a narrow precipitation band forming off the eastern shore of Lake Michigan near Ludington, Michigan at around 0245 UTC (Figure 4.5a), reaching northern parts of Chicago at 0345 UTC (Figure 4.5b). The combination of the cold, arctic air mass, above-freezing water temperatures, and northerly wind direction triggered an unusual lake-effect snow event for the Chicago area. This snow band was particularly strong not only due to the extremely cold air that was in place, but also due to the unfrozen water along the long wind fetch; the distance between Ludington and Chicago is approximately 155 miles, making the path of the fetch sufficiently large to allow a great deal of vertical moisture transport.

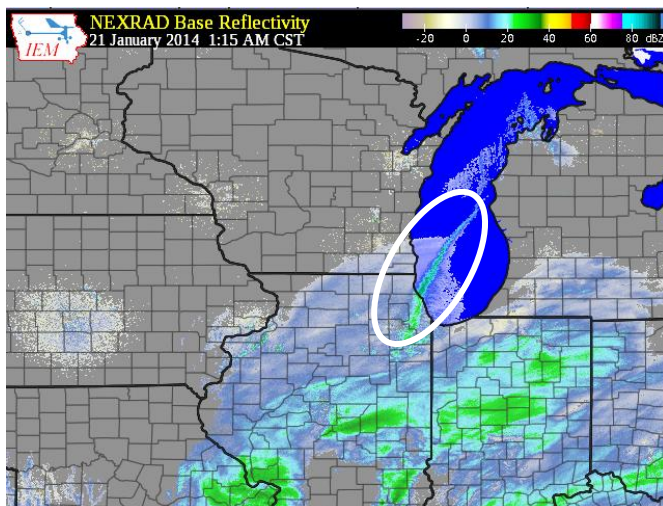
Breezy conditions developed in Chicago, with surface wind speeds fluctuating between 18 and 26 mph, gusting up to 34 mph at times; both airports reported blowing snow from about 0400 to 1100 UTC, with the heaviest falling between 0600 and 0900 UTC (Figure 4.5c). Visibility was reduced to less than half a mile, with only vertical visibility reported, which created near-whiteout conditions for several hours. The snow continued to fall through at least 1130 UTC when winds shifted to the north-northwest, and allowed the lake-effect snow band to move southeastward into northwestern Indiana. The city of Gary in Lake County, Indiana started reporting heavy snow at around 1145 UTC (Figure 4.5d). While the main snow event in Chicago was over by this time, cold-air advection and strong winds did not subside until a few hours later; O'Hare Airport reported  $-17^{\circ}\text{C}$  with a wind chill of  $-29^{\circ}\text{C}$  at 1400 UTC.



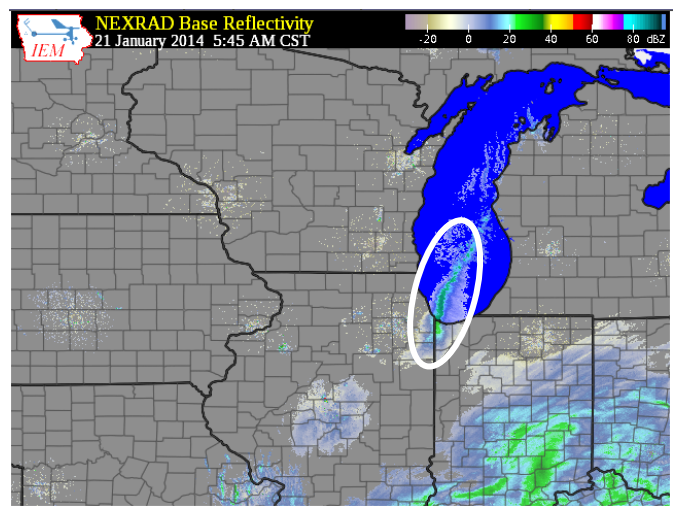
(a)



(b)



(c)



(d)

Figure 4.5. NEXRAD Base Reflectivity at different times during the event. Oval denotes the extent of the snow band. (a) 0215Z - band starting to form off the eastern shore of Lake Michigan, (b) 0315Z - band reaching the Chicago metropolitan area, (c) 0715Z - heaviest snow falling over Chicago, and (d) 1145Z - band moved eastward affecting denotes Lake County, Indiana. (Iowa Environmental Mesonet Radar Products Archives 2014).

*d. Effect on airport operations*

Both O'Hare and Midway Airports had a total of 97 delays and 22 cancellations during the lake-effect snow event, with O'Hare reporting the most. From 2300 UTC on 20 January (when snow started falling) to 1300 UTC on 21 January, about one hour after the main lake-effect snow event had finished, a total of seven flights were delayed 45 minutes or more due to weather. The longest delay was 189 minutes (of which 140 was due to weather) for a flight from O'Hare to Springfield, Missouri, which was scheduled to depart at 0400 UTC on 21 January (2200 local time on 20 January), 15 minutes after the lake-effect snow band arrived in Chicago. The flight departed at 0609 UTC (1209 local time) in the middle of blowing snow. The other six flights departed before that time, also in the middle of blowing snow.

*e. Summary*

In total, the Chicago metropolitan area received between 4 and 6 inches of snow from this event, not counting the snow that fell prior to the lake-effect band; isolated areas received 9 inches or more (Table 4.1). In the case of the 20–21 January 2014 lake-effect snow event in Chicago, the necessary ingredients for the development of this phenomenon that is uncommon in the Chicago area came together in the form of cold air advection over Lake Michigan following a frontal passage, lake surface temperatures above freezing, a significant wind fetch across the lake, and northerly wind flow.

Table 4.1. Snowfall Totals for selected stations in the Chicago area during the 20–21 January 2014 Lake-Effect Snow Event.	
Station	Accumulation (inches)
O’Hare International Airport	5.9
Midway International Airport	7.2
Downtown Chicago	6.9
Northbrook	11.8
Evanston	6.6
Park Forest	4.0

#### **4.2. Case 2: February 2011 Blizzard**

The 2010–11 winter season featured one of the most intense, devastating, and historic winter storms of all time. The “Groundhog Day Blizzard” of 2011 affected the entire Midwest region, and even areas in the Northeastern U.S., causing 36 deaths along with billion-dollar losses in both businesses and properties (LeComte 2012). The city of Chicago experienced its third snowiest storm in more than a century, with a 2-day total of 20.2 inches (Figure 4.6), while other locales dealt with heavy snow, ice, and strong winds. Between 1 and 3 February, a total of 2923 flights were cancelled in nine Midwestern airports, causing widespread disruptions across the country.



Figure 4.6. Snow-covered Lake Shore Drive in Chicago, Illinois. A historical 20.2 inches of snow fell in the city during the February 2011 blizzard. (Reuters/John Gress 2011).

*a. Synoptic setup*

The storm started as a weak surface low-pressure system in northeastern Texas/southeastern Oklahoma on 1 February; an upper low was in place over the Great Plains as well. Cold air was already present, with temperatures well below the freezing mark from the southern plains to northeastern Ohio at 1200 UTC (Figure 4.7). Surface low pressure rapidly intensified as it moved northeastward, reaching southern areas of Illinois by 1500 UTC. It was at that time that the system further intensified, as an upper-level trough began to take on more of a negative tilt, with strong pressure falls and rises being observed at the surface (NWS Chicago 2017).

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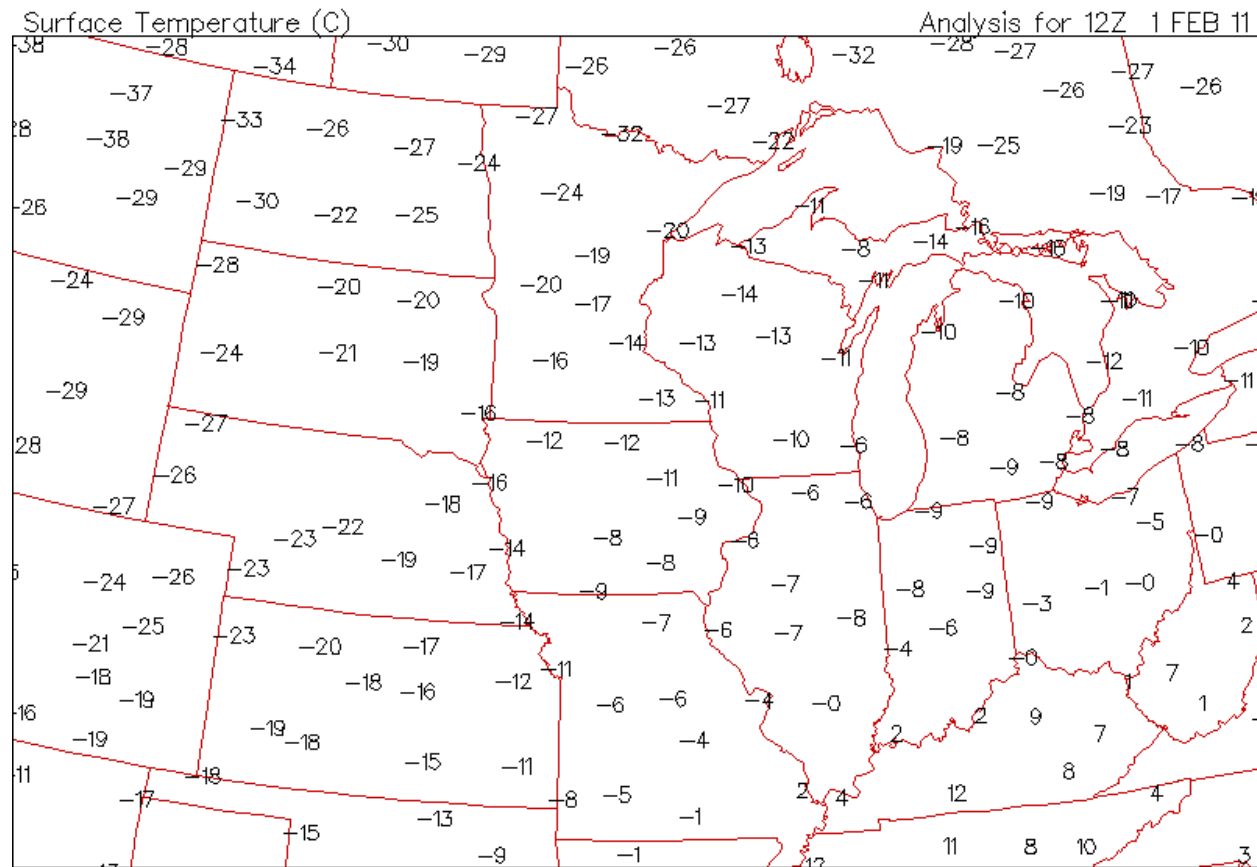


Figure 4.7. Surface Temperatures in degrees Celsius on 1 February 2011 at 1200 UTC.

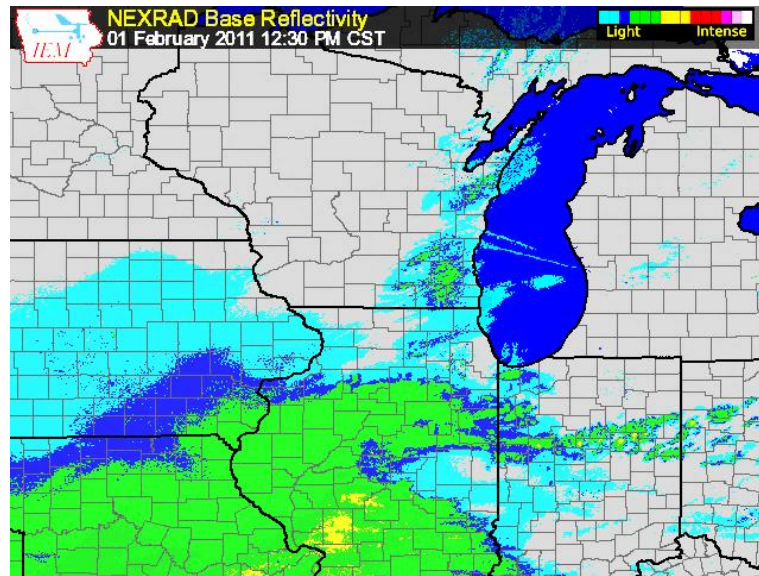
(Plymouth State University Weather Center 2011).

### *b. The blizzard event*

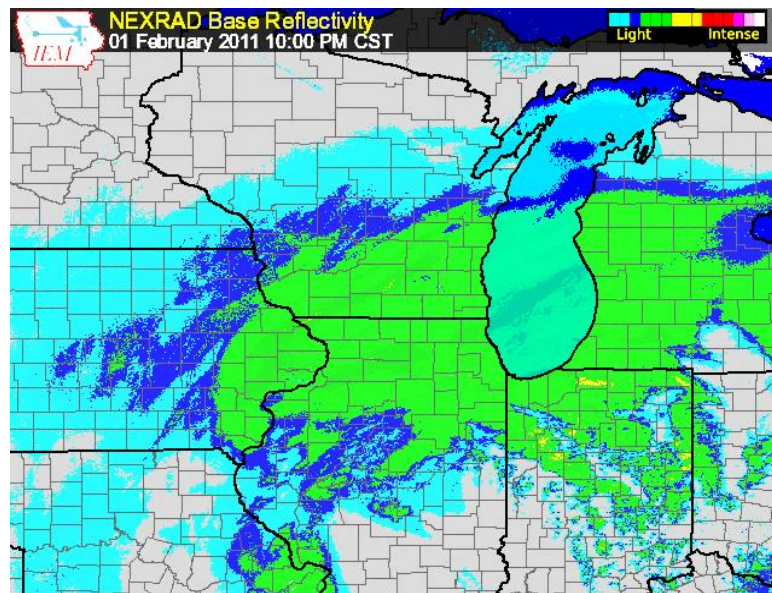
Midwestern cities started to feel the effects of the storm by 1830 UTC on 1 February, with heavy snow spreading from northern Missouri into Wisconsin, Illinois, and Indiana (Figure 4.8a). In preparation for the storm, most airlines cancelled flights at most Midwest airports before the actual system arrived in the area, while other flights were cancelled as conditions began to deteriorate. As an example, just after 2100 UTC Chicago, Milwaukee, and St. Louis experienced wind gusts in excess of 45 mph. By 0400 UTC on 2 February, the heaviest snowfall extended from



areas in southern Wisconsin/northern Illinois to and western Michigan/northern Indiana (Figure 4.8b).



(a)



(b)

Figure 4.8. NEXRAD Base Reflectivity at different times during the event. (a) 1800 UTC 1 February – snow spreading into Missouri, Illinois, and Indiana, (b) 0400 UTC 2 February – most of the snow now reached Wisconsin and Michigan. (Iowa Environmental Mesonet Radar Products Archives 2011).

Flight cancellations in all nine airports began as early as 1000 UTC on 1 February in Chicago, and although most of the heaviest snowfall was over by late 2 February, cancellations continued until around 1600 UTC on 3 February. Table 4.2 presents a summary of the cancellations that occurred during this event. The storm movement is clearly evidenced in it, as the amount of cancelled flights increases as the storm approached each airport, and it decreases as the storm moves away.

Table 4.2. Number of cancelled flights per day per airport, and the storm's 3-day total cancellations.				
<b>Airport</b>	<b>1 Feb</b>	<b>2 Feb</b>	<b>3 Feb</b>	<b>3-Day Total</b>
<b>CLE</b>	61	55	7	123
<b>CMH</b>	45	32	11	88
<b>DTW</b>	50	106	14	170
<b>IND</b>	74	51	6	131
<b>MCI</b>	102	80	11	193
<b>MKE</b>	47	101	25	173
<b>MSP</b>	66	62	9	137
<b>ORD</b>	481	818	360	1659
<b>STL</b>	149	91	9	249
<b>All Airports</b>	1075	1396	452	2923

### *c. Summary*

The NCEI developed and applies the Regional Snowfall Index (RSI) to significant snowstorms that impact the eastern two thirds of the United States. The RSI ranks impacts on a scale from 1 to 5, like the Fujita scale for tornadoes or the Saffir-Simpson scale for hurricanes. After further analysis by NCEI, the February 2011 blizzard was ranked as a “5”, classifying it as “Extreme” after scoring a RSI of 21.99 (minimum required for a “5” is 18), and as of April 2017, it ranks as the third most impactful winter storm in history for the Ohio Valley region, and the ninth most impactful storm in the Upper Midwest (NCEI 2017). At its peak, the blizzard impacted a swath of the U.S. that was over 2500 miles long and 700 miles wide with snow, sleet, and ice from southeastern New Mexico to northern Maine (Bachmeier 2017). Blizzards are not uncommon during winters and have become more frequent in the past decades. Coleman and Schwartz (2017) conducted a study on the spatiotemporal trends of blizzards which revealed that a total of 713 blizzards occurred between 1959 and 2014, with a mean of 13 events per season. Seasonal blizzard frequency ranged from one blizzard in the winter of 1980–81 to 32 blizzards in the winter of 2007–08.

Furthermore, any combination of heavy snowfall, winds, or ice is likely to affect every aspect of society by effectively paralyzing daily activities. According to Call (2010), besides disrupting both air and ground transportation, ice storms also disrupt schools, businesses, and industries, such as agriculture and timber. Between the Ohio Valley and the Upper Midwest, the February 2011 blizzard affected a total population of 64,700,387 and caused the cancellation of 2,359 flights across the region.

## **CHAPTER 5: CONCLUSIONS**

The purpose of this study was to identify the meteorological factors that prompted flight delays and cancellations during the winter season in the Midwest region of the United States. Due to the high latitude of the area, winter conditions may extend from mid-November to mid-March, bringing high amounts of wintry precipitation, strong winds, and extended periods of cloudiness and cold temperatures. Aviation is one of the primary areas affected by these hazards, prompting the delay or cancellation of flights. In order to discover the exact causes of flight delays and cancellations, data from 10 winter seasons (2005–06 to 2015–16) were analyzed to determine the meteorological factors that most affected airport operations in the Midwest, an area that hasn't been studied regarding this topic. Since winter weather conditions may be experienced both very early and very late in the season, the period of 15 November to 15 March was selected to conduct this study. Data were collected from several sources such as the Bureau of Transportation Statistics, Federal Aviation Administration, Iowa Environmental Mesonet, and the National Centers for Environmental Information.

Airport selection was performed using a list of the largest airports by passenger boardings in the nation; nine airports in the region were selected. All states in the Midwest, except for one, had at least one airport included. Due to the large disparity between their sizes, airports were further divided into two categories: large and small. For delays at large airports, a sample of the 35 days with the most delays was taken from each airport, while for small airports the top 10% of delayed flights per day were used. Finally, to correctly assess meteorological data, delays and cancellations were analyzed differently.

Results revealed that visibility reductions of 3 miles or less due to snowfall was the meteorological factor that caused the most delays in the nine airports studied. When joining all low visibility and low ceilings categories into one, low ceilings and visibility were the two main factors that affected airport operations in the Midwest during the winter season. Likewise, visibility was the factor with most delay days per factor. Although there was a marked difference between airport sizes, both large and small airports shared the overall distribution of flights delayed by factor, with low visibility due to snowfall as the main factor for delays. If one were to look at the snowfall climatology of the area, it would not be surprising that this type of winter precipitation was the cause for lowered visibilities in the region. Blizzards were the most common cause for cancellations, with more than half of them occurring during this type of weather event. Likewise, the most days with cancellations occurred during blizzard conditions. By being the most hazardous weather event among the cancellation categories, blizzards were the most likely to affect the most flights in the area.

The study period (15 November to 15 March) was effective in not only capturing the essence of the season, and thus providing enough data to conduct the study, but also drawing a variety of weather-related events, including thunderstorms, which are not common during the colder months. Dividing airports by size proved to be very useful, as not all airports handle the same quantity of flights and passengers, and if left all grouped in one single group, results would have been biased towards the larger airport, in this case, Chicago. If this were the case, the research would have neglected the region's smaller airports, and the purpose of the study would not have been achieved.

This study could serve as a guideline for potential travelers, airlines, and airports who may use it to better understand weather conditions surrounding winter in the Midwest, and how to

foresee possible delays due to low visibilities. Winter weather researchers could also benefit from this study, as it may serve as a climatological record for the area, and as proof of how strong winter storms can affect a society's day-to-day activities. The study may be extended by focusing on Midwestern airports in the 51–100 positions of the FAA list, which may provide a better insight on smaller airports by having a larger sample of them. Other future work may include focusing exclusively on specific holidays such as Thanksgiving and Christmas, dates when there are generally more travelers.

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